

AD 741505

THE CONTROL OF OXIDES OF NITROGEN EMISSIONS FROM AIRCRAFT GAS TURBINE ENGINES

Volume 1: PROGRAM DESCRIPTION AND RESULTS

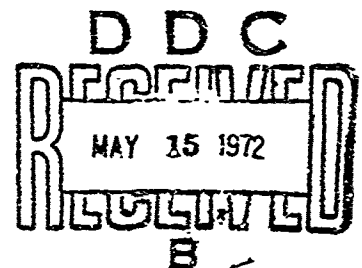
Ronald S. Fletcher
Richard D. Siegel E. Karl Bastress
NORTHERN RESEARCH AND ENGINEERING CORPORATION
219 Vassar Street
Cambridge, Massachusetts 02139



U.S. International Transportation Exposition
Dulles International Airport
Washington, D.C.
May 27-June 4, 1972

DECEMBER 1971
FINAL REPORT

Availability is unlimited. Document may be released to the National Technical Information Service, Springfield, Virginia 22151, for sale to the public.



Prepared for

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

Systems Research & Development Service
Washington, D.C. 20591

ENVIRONMENTAL PROTECTION AGENCY

Office of Air Programs
Ann Arbor, Michigan 48105

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
Springfield, Va. 22151

The contents of this report reflect the views of Northern Research and Engineering Corporation which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Department of Transportation or the Environmental Protection Agency. This report does not constitute a standard, specification, or regulation.

ACCESSION IN	
QSTI	WHITE SECTION <input checked="" type="checkbox"/>
QDC	SOFT SECTION <input type="checkbox"/>
PLANS/INDEX	<input type="checkbox"/>
NOTIFICATION	
DISTRIBUTION/AVAILABILITY CODES	
DIST.	AVAIL. NO./W SPECIAL
A	

1. Report No. FAA-RD-71-111-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle THE CONTROL OF OXIDES OF NITROGEN EMISSIONS FROM AIRCRAFT GAS TURBINE ENGINES VOLUME 1: PROGRAM DESCRIPTION AND RESULTS		5. Report Date December, 1971
7. Author(s) Ronald S. Fletcher Richard D. Siegel E. Karl Bastress		6. Performing Organization Code
9. Performing Organization Name and Address Northern Research and Engineering Corporation 219 Vassar Street Cambridge, Massachusetts 02139		8. Performing Organization Report No. 1162-1
10. Sponsoring Agency Name and Address Department of Transportation Environmental Protection Federal Aviation Administration Agency Washington, D. C. 20590 Ann Arbor, Michigan 48105		10. Work Unit No.
		11. Contract or Grant No. DOT FA70WA-2428
		13. Type of Report and Period Covered Final Report: June, 1970-December, 1971
15. Supplementary Notes		14. Sponsoring Agency Code

16. Abstract The objective of this study was to develop criteria for use in the design of aircraft gas turbine combustion chambers to minimize nitrogen oxide emissions. The approach adopted involved the development of a mathematical model of NOx emission from aircraft engine combustors; a parametric analysis, using the model, to determine the sensitivity of NOx emissions to variations of model parameters and engine design variables; evaluation of critical model parameters by means of experimental measurements; and the incorporation of the model into combustor design methods to provide guidelines for minimizing NOx emission while maintaining other performance and emission characteristics. The results of the study and the NOx emission control criteria are described in Volume 1 (FAA-RD-71-111-1). Volume 2 (FAA-RD-71-111-2) describes the nitric oxide formation process and a computer program (NOXRAT) for calculating thermodynamic data. The program is based upon a six-reaction model of NO formation. Volume 3 (FAA RD-71-111-3) describes combustion and flow processes in gas turbine combustors and a computer program (GASNOX) for calculating gas properties and NO concentrations throughout a combustor. This program is based upon a three-zone, heterogeneous model of gas turbine combustor operation. Program GASNOX is used with input data from Program NOXRAT to calculate NO emission rates.

17. Key words Air Pollution Gas Turbine Nitrogen Oxides Theoretical Model Nitric Oxide Experimental Measurement Aircraft Design Criteria		18. Distribution Statement Availability is unlimited. Document may be released to the National Technical Information Service, Springfield, Virginia 22151, for sale to the public.	
19. Security Classif. (of this report) UNCLASSIFIED	20. Security Classif. (of this page) UNCLASSIFIED	21. No. of Pages 101	22. Price \$3.00 PC .55 SE

The study reported here was carried out under the technical direction of Dr. D. M. Dix with Dr. Ronald S. Fletcher assuming project responsibilities. Other participants in the program were Dr. R. D. Siegel, Dr. E. K. Bastress, and Mr. R. J. Murad; Professors J. B. Heywood, A. H. Lefebvre, and Mr. E. R. Norster served in a consulting capacity during the course of the study.

This study was sponsored in part by the Federal Aviation Administration and the Environmental Protection Agency under Contract No. DOT FA70WA-2428. Technical monitoring of the program was conducted by Mr. William T. Westfield (FAA) and Mr. George D. Kittredge (EPA).

CONTENTS

	Page
1. SUMMARY	1
2. INTRODUCTION	4
2.1 Background	4
2.2 Program Objective	5
3. THE EMISSIONS MODEL	7
3.1 The Nitric Oxide Formation Process	7
3.2 The Flow Model	10
3.2.1 Primary Zone Model	11
3.2.2 The Intermediate Zone	14
3.2.3 The Dilution Zone	15
3.3 Model Input Requirements	15
3.4 Summary of Model Output	17
4. PARAMETRIC STUDY	19
4.1 Model Sensitivity Analysis	19
4.1.1 Mixedness of the Primary Zone, S_0	20
4.1.2 Primary Zone Fuel-Burning Fraction,	21
4.1.3 Air Distribution Characteristics	22
4.1.4 Mixing Parameters of the Intermediate Zone	23
4.1.5 Kinetic Rate Data	24
4.1.6 Conclusions	24
4.2 Design Sensitivity Analyses	25
4.2.1 Mean Primary Zone Residence Time	25
4.2.2 Mean Primary Zone Equivalence Ratio	26
4.2.3 Pressure Ratio	27
4.2.4 Pressure Ratio Effects, Specific Fuel Consumption, Specific Thrust and Emissions	29
4.2.5 Experimental Data	30
4.2.6 Conclusions	31
5. THE EXPERIMENTAL PROGRAM	32
5.1 Test Objectives	32
5.2 Test Plan	32
5.2.1 Test Series 1 - Combustor A	33
5.2.2 Test Series 2 - Combustor B	33
5.3 Experimental Equipment	34
5.3.1 The Combustor Testing Facility	34
5.3.2 Sampling Methods	34
5.3.3 Instrumentation	35
5.4 Summary of Results	36
6. COMPARISON BETWEEN MODEL PREDICTIONS AND EXPERIMENTAL RESULTS	37
6.1 Model Input Data	37

CONTENTS ,CONTINUED,

	Page
6.1.1 Combustor Characteristics	37
6.1.2 Combustor Operating Conditions	37
6.1.3 Primary Zone Mixing Parameter	38
6.1.4 Kinetic Constants	39
6.2 Model Verification	40
6.2.1 Comparison with Combustor A	41
6.2.2 Comparison with Combustor B	42
6.2.3 Comparison at Low Power (Idling) Conditions	44
6.3 Conclusions	45
7. DESIGN CRITERIA	46
7.1 The Combustor Design Problem	46
7.1.1 Performance Requirements	46
7.1.2 Design Procedures	47
7.1.3 NOx Emission Control	50
7.2 Conventional Combustors	51
7.2.1 Performance Characteristics	51
7.2.2 Designing for NOx Control	52
7.3 Alternative Approaches to NOx Emission Control	56
7.3.1 Use of Water Injection	56
7.3.2 Variable Geometry Combustor Design	58
7.3.3 Staged Combustion	58
7.4 Conclusions	59
8. REFERENCES	61
9. TABLES	63
10. FIGURES	72
11. NOMENCLATURE	100

LIST OF TABLES

	Page
1 COMBUSTOR CONDITIONS INVESTIGATED IN THE MODEL SENSITIVITY ANALYSIS	64
2 KINETIC DATA FOR THE NITRIC OXIDE REACTION SCHEME	65
3 CHANGES IN NITRIC OXIDE EMISSION LEVELS PREDICTED USING FOUR ALTERNATIVE SETS OF KINETIC DATA	66
4a SUMMARY OF TEST DATA - COMBUSTOR A	67
4b SUMMARY OF TEST DATA - COMBUSTOR A	68
5a SUMMARY OF TEST DATA - COMBUSTOR B	69
5b SUMMARY OF TEST DATA - COMBUSTOR B	70
5c SUMMARY OF TEST DATA - COMBUSTOR B	71

LIST OF FIGURES

	Page
1 ASSUMED FLOW AND DISTRIBUTION PATTERNS THROUGHOUT COMBUSTOR LINER	73
2 THE EFFECT OF PRIMARY ZONE MIXEDNESS UPON NITRIC OXIDE EMISSION LEVELS	74
3 EFFECT OF PRIMARY ZONE FUEL-BURNING FRACTION AND DILUTION AIR MIXING RATE UPON PREDICTED NITRIC OXIDE EMISSIONS	75
4 THE EFFECT OF INTERMEDIATE ZONE MIXING BEHAVIOR UPON NITRIC OXIDE EMISSION LEVELS	76
5 EFFECT OF PRIMARY ZONE RESIDENCE TIME ON NO _x EMISSION PREDICTIONS	77
6 EFFECT OF PRIMARY ZONE EQUIVALENCE RATIO UPON NO _x EMISSION PREDICTIONS	78
7 EFFECT OF ENGINE PRESSURE RATIO UPON NO _x EMISSION PREDICTIONS	79
8 MEASURED EFFECT OF ENGINE PRESSURE RATIO UPON NO _x EMISSIONS	80
9 PRIMARY ZONE COMBUSTION EFFICIENCY CORRELATION	81
10 COMBUSTOR TEST ARRANGEMENT	82
11 THE TEST FACILITY	83
12 THE TEST CONTROL ROOM	84
13 SCHEMATIC DIAGRAM OF EQUIPMENT EMPLOYED IN EMISSIONS SAMPLING AND ANALYSIS	85
14 AIR DISTRIBUTION CHARACTERISTICS	86
15 PRIMARY ZONE OPERATING CHARACTERISTICS	87
16 PREDICTED VERSUS MEASURED NITRIC OXIDE EMISSIONS	88
17 PREDICTED TEMPERATURE, TIME, EQUIVALENCE-RATIO AND NITRIC OXIDE PROFILES WITH AXIAL POSITION	89
18 PREDICTED VERSUS MEASURED NITRIC OXIDE EMISSIONS (COMBUSTOR A. P. = 35)	90

LIST OF FIGURES (CONTINUED)

	Page
19 PREDICTED VERSUS MEASURED NITRIC OXIDE EMISSIONS (COMBUSTOR A, $P = 120$)	91
20 PREDICTED VERSUS MEASURED NITRIC OXIDE EMISSIONS (COMBUSTOR B, $P = 85$)	92
21 NITRIC OXIDE EMISSIONS AT LOW POWER LEVELS (COMBUSTOR B)	93
22 COMBUSTION PERFORMANCE MAP FOR FIXED AND VARIABLE GEOMETRY COMBUSTORS	94
23 EFFECTS OF FUEL DISTRIBUTION ON PREDICTED NO EMISSION RATE (COMBUSTOR B)	95
24 PREDICTED NITRIC OXIDE EMISSIONS MAP (COMBUSTOR B)	96
25 PERFORMANCE MAP FOR MODIFIED-COMBUSTOR DESIGN PROCEDURE (COMBUSTOR B)	97
26 ESTIMATED EFFECT OF WATER INJECTION (COMBUSTOR A)	98
27 ESTIMATED EFFECT OF WATER INJECTION (COMBUSTOR B)	99

1. SUMMARY

It has been established from earlier studies that aircraft engine pollutant emissions are becoming a more significant factor in regional pollutant levels and are already of concern in the communities adjacent to the major air terminals. The pollutant classes to be contended with have been shown to be carbon monoxide, the hydrocarbons, nitrogen oxides (NO_x), and particulates. Of these, the only pollutant class for which control criteria do not exist are the nitrogen oxides, and the object of this study was to produce such criteria as might apply to the range of aircraft gas turbine engines that are in use, or in the planning phase today.

The method of approach adopted to develop the design criteria involved four separate studies with the following objectives:

- a. The development of a computerized mathematical model of NO_x emission from aircraft engine combustors.
- b. A parametric analysis; using the model, to determine the sensitivity of NO_x emission to variations of model parameters and engine design variables.
- c. Evaluation of critical model parameters by means of experimental measurements.
- d. The incorporation of the model into existing combustor design methods to provide guidelines for minimizing NO_x emission while maintaining other performance characteristics at satisfactory levels

The mathematical model presented is based upon a relatively simple approach to the problem and its validity rests upon two main assumptions: firstly, that the combustion process is mixing controlled and therefore, that equilibrium conditions occur for the main species of interest in the nitric oxide formation process; and secondly, that the degree of imperfect mixing in the hot zones of the combustor can be represented statistically by a Gaussian distribution in fuel-air ratio. Based on these assumptions, the model predicts distribution characteristics and the mass average values of nitric oxide concentrations, temperature,

fuel concentrations, and residence times at all regions throughout the combustor.

The computer model was first tested with a parametric study and it involved both a model sensitivity analysis, which established the relative importance of certain parameters such as the mixing parameters which are internal to the computing procedure, and then a design sensitivity analysis. This latter analysis chiefly established the importance of the combustor operating conditions and showed that the engine compressor pressure ratio (or combustor inlet temperature) has the greatest influence upon the nitric oxide emission levels for a given aircraft operating condition. Of the variables under the control of the designer, the mass mean equivalence ratio and the degree of homogeneity of combustion within the hot primary zone of the combustor were established to be the most significant to control, with minimum emission levels corresponding to the lowest equivalence ratio and best mixed condition.

The predictions of the computer model were then tested against new experimental data collected during this study. The results presented are for two current aircraft engine combustors, designed by different design teams, that were operated at conditions which simulated those experienced in flight operation. The conditions applied to each combustor were made to overlap so that their nitric oxide emission characteristics could be compared. Significant differences can be observed between these combustors, and the results are found to correlate very well with the model predictions for certain prescribed values of the homogeneity of combustion in the primary zone. The homogeneity parameter is found not to dominate the predictions and the predicted results are found to be influenced more by the other combustor operating conditions.

Based on the results of these studies and predictions made by the mathematical model, a design technique is established which may be used to minimize future aircraft gas turbine engine emissions of nitric oxide. Gap areas in knowledge about combustor operating phenomena currently limit the usefulness of the technique, but it has been applied to one of the combustors tested to estimate the potential reduction in nitric oxide emissions that might be attained if the technique were employed.

Alternative methods of nitric oxide control are considered and the potential effectiveness of each control method is evaluated in certain cases. The alternative control methods considered are water injection, variable geometry, and staged combustion.

On the basis of the results of this study, the following conclusions have been formulated:

- a. NOx emission rate can be related to fundamental combustor design parameters which also influence other major combustion performance factors. This interrelationship between NOx emissions and other combustion performance factors provides a basis for quantitative NOx emission control criteria.
- b. NOx emission rates from conventional combustors can be reduced by modification of fuel distribution parameters. However, NOx reduction may be accompanied by significant reductions in other performance factors such as combustion efficiency and reignition altitude. These performance losses are more severe in a modified-combustor design procedure where combustor size is fixed than in a new-combustor design procedure.
- c. Water injection is effective in reducing NOx emissions from conventional combustors. Emission rate reductions of approximately 50 per cent at high power levels can be obtained with water injection rates equal to fuel injection rates. Increased control may be obtained with increased water injection rates, or by localizing injection of water into the combustion zone.
- d. Advanced combustor design concepts, such as variable geometry or staged combustion, show promise of effective NOx emission control for future engines. The degree of NOx emission control attainable using either of these concepts is estimated to be of the same order as that attained by water injection.

All the results of this study are presented in Volumes 1, 2, and 3 of this report. Volume 1 describes the complete program, but precise details of the mathematical model and the computer programs developed from the model are presented in the other volumes. Volume 2 describes the theory and computer program for determining nitric oxide formation rates, and Volume 3 the corresponding information for the flow model used to determine the nitric oxide emission level.

The rates of pollutant emission by aircraft are increasing with time as a result of increases in aircraft activity and certain changes in equipment, including size, engine type, and performance characteristics. Thus, aircraft emissions are becoming a more important factor in regional pollution levels. This trend will continue until criteria are developed for reducing emissions, and standards are set to limit emission rates.

Design methods exist today for minimizing emissions of carbon monoxide and hydrocarbons (Ref 4). The successful application of these methods at medium and high power operation conditions has resulted in high efficiency and low emission rates during aircraft flight operations. The application of these design methods to low power conditions should reduce emissions of CO, hydrocarbons, and possibly odor by aircraft engines during ground operations. Methods of reducing these "low power emissions" are being developed currently by the Pratt & Whitney Aircraft Division of the United Aircraft Corporation for the Air Force Aero Propulsion Laboratory.

Design methods of an empirical nature exist for reducing the emission of particulates by aircraft turbine engines. These methods have been utilized in the past in the development of combustion chambers in order to achieve maximum chamber durability and to reduce carbon deposition throughout the engine. More stringent applications of these same methods are serving to reduce visible smoke emission from contemporary engines.

The only pollutants for which control criteria do not exist are the nitrogen oxides. Because of this lack of NO_x control criteria, it is not possible to predict accurately the effects of engine design changes on rates of NO_x emission. However, it is clear that current trends toward increased engine power levels and operating temperatures will result in higher NO_x emission rates unless control criteria are developed.

2.2 PROGRAM OBJECTIVE

The objective of this study was to develop criteria which may be used during the design of aircraft gas turbine combustion chambers to minimize the emissions of nitrogen oxides.

To be useful, design criteria for NO_x control must provide quantitative relationships between design variables and emission rates. Such criteria can be developed by empirical analysis of large quantities of engine design and emission data, or by theoretical analysis of combustor performance supported by limited experimental data. The method adopted for this program is based on the latter approach, since it is considered to be a more effective and economical approach to this particular problem.

Having selected the theoretical analysis approach, two alternatives present themselves. A highly accurate and comprehensive model of NO_x emission might be selected as the program goal, in which case complete achievement of the goal in the initial program could not be assured. Alternatively, one might set out to develop a simpler but still valid NO_x emission model and then to evolve design criteria based upon this model. This latter alternative was selected as a goal which could be achieved with a reasonable amount of effort.

Thus, the problem to which this study was addressed is the development of criteria for relating NO_x emissions to engine design and performance characteristics, and the method of approach adopted involved four separate studies with the following objectives:

- a. The development of a computerized mathematical model of NO_x emission from aircraft engine combustors.
- b. A parametric analysis, using the model, to determine the sensitivity of NO_x emission to variations of model parameters and engine design variables.
- c. Evaluation of critical model parameters by means of experimental measurements.
- d. The incorporation of the model into existing combustor design methods to provide guidelines for minimizing NO_x emission while maintaining other performance and emission characteristics.

Volume 1 of this report describes the methods used to satisfy these objectives and also the results obtained from all four tasks described above. Details of the mathematical model and the computer program developed from the model are fully described in Volumes 2 and 3.

3. THE EMISSIONS MODEL

Calculations based upon NO_x kinetics clearly show that for measurable concentrations of nitric oxide to be formed during the short time it takes the gases to pass through an aircraft gas turbine engine, the temperature must exceed 2000 deg K. Such high temperatures only exist within the combustor, and only then for a limited time, so clearly, nitric oxide concentrations in the exhausts of aircraft engines are solely dependent upon the flow behavior and the chemical processes occurring within the combustion chamber and it is these features that need to be adequately represented in the model. The important chemical reactions and their reaction rates must be known and a rate equation for nitric oxide formation derived from these data. A flow model also has to be developed to predict the thermodynamic states of the gases inside the combustor inner. The gas temperature, density, and concentrations of species important in the nitric oxide formation process must then be determined and the rate equation integrated through this sequence of thermodynamic states.

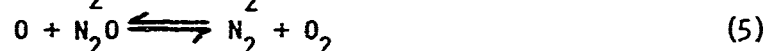
Conveniently, the two parts can be separated for two reasons. Firstly, nitric oxide concentrations are sufficiently low so that changes in concentration have a negligible effect upon the gas temperature. Secondly, the nitric oxide formation process proceeds more slowly than fuel combustion processes so that most nitric oxide is formed after concentrations of other combustion products have reached equilibrium levels. The nitric oxide formation process and combustor flow processes are considered separately below.

3.1 THE NITRIC OXIDE FORMATION PROCESS

Engine exhaust emissions are often expressed as nitrogen oxides (NO_x), or as nitrogen dioxide (NO₂). However, at the high power conditions, the pollutant present in the exhaust gas as it leaves the engine is almost completely nitric oxide (NO, with only a few per cent of NO₂ (Ref 5). At low engine power levels, the percentage of NO₂ present can increase significantly but at these conditions the total NO_x concentration is very low, hence, the NO₂ contribution is not

significant when compared to levels of total NO_x emissions which are of interest today. The conversion to NO_x or NO₂ is made because many of the early techniques used to measure nitric oxide required first that it be oxidized to nitrogen dioxide. Thus, inside the engine, the important oxide of nitrogen to consider is nitric oxide, NO.

There are many reactions schemes proposed in the literature for nitric oxide formation (Refs 5-8) and they are reviewed in Volume 2, Section 2 of this report and in Reference 9. The reaction scheme employed in these studies and incorporated into the flow model is as shown below:



Each of the six reactions proceeds at a different reaction rate which can be defined by a general rate term of the form

$$k_i = A_i T^{n_i} \exp(-E_i/RT) \quad (7)$$

where k_i is the reaction rate constant for the equation i

T is temperature

R is the universal gas constant

and A , n , and E are empirical constants which need to be determined by experiment. Many values are given for these constants in the literature and these too are reviewed in Volume 2, Section 2, and four different sets of data are isolated.

In general, one can show that not all of the above reactions contribute significantly to the formation of nitric oxide over the conditions encountered in the aircraft gas turbine engine. The contributions by the first two reactions (Equations 1 and 2), often

referred to as the Zeldovich chain mechanism, are by far the most significant. The third reaction can become important under particular operating conditions, such as when parts of the fuel charge burn in the presence of an insufficient quantity of air, but simple calculations show that reactions 4, 5, and 6 do not contribute greatly to the nitric oxide formation rate. However, in the interest of completeness, all reactions have been included in the computerized model and their individual contributions studied as part of the second phase of this program (see Section 4.1).

In order to apply this reaction scheme to gas turbine combustors, it is necessary to be able to predict the concentration levels of all species active in the set of six reactions specified above at all thermodynamic states typical of the combustor. At the pressure and temperature levels that exist in such combustors during high thrust, low altitude operation, the hydrocarbon oxidation reactions go rapidly to completion compared with the nitric oxide formation processes. In order to predict these specie concentrations therefore, the following assumptions are made:

- a. Combustion is mixing controlled and not reaction rate-limited, and therefore, that in the combustor, N_2 , O_2 , O , OH , H , and H_2 concentrations are the equilibrium concentrations corresponding to the combustor inlet temperature and pressure, and to the equivalence ratio. This assumption limits the usefulness of the model to high pressure, high temperature operating conditions, but it is precisely these conditions at which most nitric oxide is produced and are therefore of most interest to this study.
- b. N and N_2O concentrations are given by the steady-state assumption; that these concentrations are not in equilibrium but are in steady-state with NO can be shown by deriving rate equations for N and N_2O which have relaxation times short compared with the NO rate equation.

If these assumptions are applied to Equations 1 through 7, then the change in total nitric oxide per unit time per unit volume that results from chemical reaction over a fixed element can be expressed as a function solely of the local nitric oxide concentration and the local pressure, temperature, and chemical specie compositions (see Equation 8, Volume 2, Section 2). If a flow model is now developed which can predict values of these latter variables throughout the gas turbine engine, then the generation of nitric oxide can be calculated by integration of the chemical rate function.

3.2 THE FLOW MODEL

The flow model under consideration has to be applied to both canannular and annular combustors and to take into account the two distinct functions performed in their operation. These are the rapid mixing between fuel and air, flame stabilization, and combustion processes occurring in the primary zone, and the combustion gas cooling by mixing with dilution air before entry into the turbine in the secondary zones. Figure 1a is a schematic of the mean flow pattern illustrating these two functions. The flow characteristics in each zone are significantly different.

In the primary zone, a mean flow pattern with recirculation approximately as shown in Figure 1a can be defined. However, substantial turbulent fluctuations about this mean occur, resulting in wide variations in residence time and composition within the zone. The fuel, air, and combustion products are not uniformly mixed, and parts of the flow are significantly leaner and parts are richer than the mean fuel-air ratio. One result of this incomplete mixing is that some unreacted fuel leaves the primary zone. Even at full power, low altitude, operation when the kinetics of the hydrocarbon oxidation process are not important, less than 90 per cent of the fuel fed to the primary zone is burned^{*} there.

* The term "burn" is used throughout this report to represent the processes of ignition and reaction of fuel-air mixtures to form combustion products of equilibrium composition (except for NO). Burning is assumed to occur instantaneously upon mixing of fuel and air

In the rest of the combustor, the remaining fuel is burned, and diluting air is mixed with the primary zone products. While turbulent fluctuations are significant, the flow is primarily unidirectional. Typically, dilution air is added both through large holes in the liner so that air jets penetrate to the core of the combustion products flow, through smaller holes so that mixing occurs at intermediate radii, and along the walls for film cooling. Thus, at combustor exit, the gases are sufficiently well mixed to obtain the desired temperature profile across the flow before entry to the turbine. Separate flow models are required for these different parts of the combustor. Figure 1 illustrates the division of the liner into three zones and the model used in each zone. These models are described qualitatively below and full mathematical details are presented in Volume 3, Section 2, of this report.

3.2.1 Primary Zone Model

The hottest zone in a gas turbine combustor is normally the primary zone. It is the zone where fuel and air are injected at an approximately stoichiometric mixture strength and where most of the combustion takes place. The fuel is sprayed from an atomizing fuel nozzle and strategically located jets cause the incoming air to generate a recirculating flow of the type shown schematically in Figure 1a. It is a region of intense turbulent combustion and the process is so complex that it is not possible to produce a complete analytical (i.e., mathematical) description of the time sequence of events.

One analytical approach used to represent reacting systems such as that above is to adopt the concept of a perfectly stirred reactor. That is to assume that the reactants mix instantaneously to the perfectly mixed state before reaction proceeds. It is clear that such a reactor is an ideal concept that can only be approached in practical systems since mixing develops at a finite rate. The application of this concept to the problem under study can be anticipated to be totally inadequate since:

- a. The mixing process, involving reactants in different phases, takes a long time relative to the combustion process and causes combustion to take place between imperfectly mixed reactants.
- b. Primary zone equivalence ratios are typically about unity. Distributions in the fuel-air ratio about this mean value substantially change the concentrations of the major chemical species and temperatures, and can be shown (from Equations 1 through 7) to drastically influence nitric oxide formation rates.

Hence, the effect of imperfect mixing must be taken properly into account.

In addition to the calculation of nitric oxide formation rate, it is also necessary to determine the time the reactants spend in the primary zone, that is the residence time. For the perfectly stirred reactor, this presents no problem as one can show mathematically that there must be a distribution of residence times in an exponential form related to the volumetric flow rate and the volume of the reactor (see Volume 3, Section 2). This same distribution of residence times will be assumed to be applicable as it has been shown that most practical systems do in fact exhibit this property.

The problem in developing an adequate model for the combustion in the primary zone, therefore becomes one of accounting for the nonuniformities in concentration that exist at the onset of combustion. It is assumed here that the flow into the primary zone rapidly mixes to a scale small compared with combustor dimensions, but not complete on a molecular scale, such that there exist discrete eddies of different mixtures which burn and retain their identity throughout their passage through the primary zone. As the scale of mixing is assumed small, it is consistent to assume that the nonuniformities in concentration can be represented by a Gaussian distribution function as shown in Figure 1c.

The "mixedness" of the primary zone can then be characterized by the single dimensionless parameter $S_0 = \sigma_F / \bar{F}$ where σ in statistical terms is called the standard deviation and represents the degree of distribution of F about \bar{F} so that the quality of mixing decreases

as the parameter S_o increases. (It should be noted that $S_o = 0$ corresponds to the perfectly mixed case, i.e., to the perfectly stirred reactor.) At the present, the value of S_o can only be estimated, but clearly it is related to the energy supplied to the primary zone by the air and fuel jets. Its value together with those of other design variables, is first treated parametrically in the initial computer analysis presented in Section 4, and one of the objectives of the experimental program described in Section 5 is to isolate its value for the two combustor tests.

As previously discussed, not all the fuel supplied to the primary zone actually burns in the zone. Account is taken of this fact simply by modifying the mass-mean mixture ratio \bar{F}_p , calculated from the fuel and airflow rates into the zone. The fraction of fuel burned, represented by the symbol β , is calculated from the correlation shown in Figure 9, taken from Reference 15. This correlation is based upon measured primary zone combustion efficiency (η_{cp}). Since combustion efficiency is reduced both by nonburning and partial-burning of fuel, the use of this correlation to calculate the fraction of fuel burned introduces an error into the analysis. The effects of partial-burning of fuel are introduced through the mixture ratio distribution factors \bar{F}_p and S_o since partial-burning results primarily from the use of rich mixtures or poor mixing. Therefore, β should be evaluated on the basis of nonburned fuel only. However, data on nonburned fuel at the primary zone exit, as distinguished from primary zone efficiency, are not available. Hence, the efficiency correlation is used to calculate β and the error thus introduced is noted; that is, qualitatively, β should be somewhat higher than η_{cp} . The unburned fuel is assumed to burn in the intermediate zone in a manner as described below.

Combustion dimensions, airflow distribution characteristics, operating conditions, and a prescribed value of the mixedness parameter are all that are needed to calculate the mass average nitric oxide concentration at the exit from the primary zone.

3.2.2 The Intermediate Zone

The intermediate zone represents a transition between the primary and dilution zones as shown in Figure 1a. Mixing occurs in this zone between the heterogeneous products from the primary zone and the entering secondary combustion air which, in practice, is usually added sufficiently slowly to allow recombination of the dissociated combustion products and burn-up of the remaining unburned fuel to occur. The basic assumption made in modeling the flow is that in the prescribed length, L , complete mixing occurs between all elements leaving the primary zone, secondary air added to the zone, and all fuel not burned in the primary zone. Entry conditions to this zone correspond to time-average primary zone exit conditions; at zone exit the flow is homogeneous and the flow velocity is assumed to be one-dimensional. It should be noted that the value of L can be greater than the length of the combustor, in which case complete mixing will not occur within the system.

The mixing conditions in this zone can be represented schematically as shown in Figure 1b. The mass-average mixture ratio usually decreases from that at the primary zone exit due to the addition of more air through holes in the liner wall and the degree of unmixedness steadily decreases. In order to follow the change in nitric oxide concentration along the zone, the following assumptions are made concerning the mixing behavior (see Volume 3, Section 2):

- a. That the rate of mixing to the homogeneous state is proportional to the square root of the distance traveled from the primary zone exit.
- b. That the unburned fuel leaving the primary zone follows the same mixing law as for (a) and is instantaneously burned at the time of mixing.
- c. That air entering the intermediate zone through the liner wall is distributed among all flow elements in proportion to the masses of the elements, and that mixing of this air occurs at a finite rate according to the same mixing law as for (a).
- d. That intermixing occurs between elements of different nitric oxide concentration, and the rate of mass flow from an element due to intermixing is proportional to the mass of the element.

Justification for the first two assumptions rests with the fact that the mixing rate is known to be proportional to \sqrt{t} , i.e., is approximately proportional to \sqrt{X} and it is this type of mixing which is finally of importance in the reacting process. The latter two assumptions stem from the concept of combustor aerodynamics employed in this study in which the flow system is envisaged as a multitude of eddies each of which retains its identity until mixing is complete. All eddies are assumed to be similar in size (or mass) and to exchange mass with other eddies through mixing processes at similar rates. A flow element includes all eddies with fuel-air ratios within a specified range. Hence, it follows that the rate of exchange of mass among elements is proportional to the masses of the elements. The sensitivity of the results to this assumed mixing behavior is explored in Section 4 of this report.

3.2.3 The Dilution Zone

In the dilution zone, the flow is assumed to be one-dimensional with the gases uniformly mixed across each cross section. Only the mean mixture ratio need be considered, and this only changes as the remaining compressor air is mixed in. The nitric oxide mass fraction changes through chemical reaction, and through dilution as additional air is mixed with the bulk flow within the combustor liner and both factors can be taken properly into account by the method presented in Volume 3, Section 2. The exit conditions from the intermediate zone start the calculations for this zone and integration of the nitric oxide rate equation can be performed to the end of the combustor.

In practice, the state of uniform mixing as idealized above is rarely accomplished, but as the nitric oxide formation rate is reducing rapidly in this zone of the combustor, it was anticipated that the assumption would have little significance upon the levels of nitric oxide predicted to exist in the combustor exhaust.

3.3 MODEL INPUT REQUIREMENTS

In order to obtain a prediction of the nitric oxide emissions level from the model described above, the following data must be specified:

- a. Kinetic Constants: The reaction scheme for nitric oxide formation rate described in Section 3.1 has six intermediate steps. Each step, of course, has its own characteristic values for A , n , and E and these must be specified in the input data (see Table 2 for values of these parameters).
- b. Combustor Operating Conditions:
 - T - Inlet temperature
 - P - Operating pressure
 - $\bar{\Phi}_p$ - Mass mean equivalence ratio in the primary zone
- c. Combustor Dimensions:
 - V_p - Volume of the primary zone
 - X_L - Length of the intermediate zone (from the exit of the primary)
 - X_{END} - Distance from the primary zone exit to the exit from combustor liner
 - R_x - Radius of the liner at position X for all positions downstream of the primary zone exit (for annular combustors the inner and outer radii must be specified)
- d. Mixing and Combustion Parameters for the Primary Zone:
 - S_o - Degree of mixedness in the primary zone
 - β - Fraction of fuel which burns in primary zone
- e. Air Distribution:
 - M_{ax} - The fraction of the total mass flow rate of air mixed with the combustor flow stream at axial position X (calculation method given in Volume 3, Appendix XVI)
- f. Mixing Parameters for the Intermediate Zone:
 - C_N - A parameter specifying the rate of intermixing between flow elements in the intermediate zone (see Volume 3, Section 2)
 - A_1 - Defines the rate at which σ_o collapses in the intermediate zone according to the relationship: $\sigma_x = \sigma_o (1 - (X/X_L)^{A_1})$
 - A_2, A_3 - Define the rate at which unburned fuel, M_{fu} , is burned in the intermediate zone by $M_{fu} = M_{fu0} (1 - A_3 (X/X_L)^{A_2})$
Values of the three A parameters can be estimated from

turbulent mixing phenomena (see Volume 3, Section 2) to be given by

$$A_1 = 0.5$$

$$A_2 = 0.5$$

$$A_3 = 1.0$$

The value of C_N needs to be determined, but as will be shown in Section 4, nitric oxide predictions are very insensitive to the value prescribed and a value of 5 is taken as the nominal value. The effects of changes in values for A_1 , A_2 , and A_3 are also determined in Section 4.

Except for the variables $\bar{\Phi}_p$, M_{ax} , and S_o , these input parameters can be determined directly for the case(s) of interest. The methods of calculating the first two variables are described in Volume 3, Appendix XVI. The value of S_o must be determined independently for each combustor design to be analyzed. At the present time, S_o cannot be evaluated directly from combustor design characteristics, but must be estimated indirectly through comparisons of predicted and measured NO emission rates. By this means, the value of S_o has been found to lie within the range

$$0.3 < S_o < 0.7$$

for combustors of conventional design.

3.4 SUMMARY OF MODEL OUTPUT

The model described above has been programmed for solution by digital computer (see Volume 3) and the results from a typical test case have the following general form:

- a. In the primary zone the flow is considered as a series of elements each bounded by discrete steps in equivalence ratio over a range of values from 0.0 to approximately 3.0. The results specify the mass fraction and time-average nitric oxide concentration for each element at the primary zone exit together with the total mass average values of nitric oxide, temperature, and density. The characteristic residence time

and mass average equilibrium values of carbon monoxide, carbon, and hydrocarbons are also computed.

- b. The intermediate zone results are identical to those computed for the primary zone and are calculated at discrete steps taken downstream of the primary zone exit. The computations continue until the rate of production of nitric oxide becomes insignificant when compared to the earlier formation rates. If this occurs in the intermediate zone, one final computation is made to determine the conditions at the exit of the combustor; otherwise the computation continues into the dilution zone where only mass average values are computed due to the assumption that all gases are well-mixed in this zone.

4. PARAMETRIC STUDY

Those parameters which describe the combustor dimensions and operating conditions, groups b and c in Section 3.3, are reasonably well defined for any given combustor, but the groups, a, d, e, and f contain parameters that are not only less-well defined, but also are essentially internal to the computing procedure. A division was made between them therefore, and the parametric study was first concerned with the latter four groups in what is termed a "model sensitivity analysis". The objectives of this sensitivity analysis were:

- a. To determine how significant a role these parameters played in predicting NO_x emissions.
- b. To determine the best values to use for these parameters during the testing of the group b and c variables.

The second phase of the analysis is termed the "design sensitivity analysis" and is concerned with more practical aspects such as the effect of the size of the primary zone, the mean equivalence ratio in the primary zone, and the engine pressure ratio upon the levels of nitric oxide emission. Predictions obtained from this second study are compared with experimental data published soon after the study was conducted.

4.1 MODEL SENSITIVITY ANALYSIS

In order to make full use of the results obtained from the model sensitivity analysis, the selected combustor dimensions and operating conditions corresponded to those of one of the two combustors tested experimentally in the following phase of this study (see Table 1).

Nominal values were chosen for the mixing parameters and each was varied systematically to at least one value higher and one value lower than nominal while all other variables were maintained constant; thus, A_1 nominal was set equal to 0.5, but calculations were also made with values equal to 0.2 and 1.0. Values assumed for the other mixing parameters are listed in Table 1, together with those values used to represent the combustor and its operating conditions.

Four sets of data were selected for the kinetic rate constants. The sources of these data are discussed in Volume 2, Section 2, and in Reference 9. Two sets of data were arbitrarily selected as those which would predict the lowest and highest emissions of nitric oxide. The third set was used in Reference 10 for piston engine emission work. The fourth set was selected because it was the result of a comprehensive search of the literature (Ref 11). All four sets of values for the reaction rate data are given in Table 2. Additional calculations were made to determine the importance of reactions 4 to 6 (see Section 3.1) by setting their rate terms all equal to zero for each of the four sets of data.

The results obtained from this sensitivity analysis are summarized graphically in Figures 2, 3, and 4 and Table 3, are discussed below.

4.1.1 Mixedness of the Primary Zone, S_o

Model predictions (see Figure 2, lower figure) show that for the combustor under consideration, the value assumed for the mixing conditions in the primary zone does not play a very significant role in the level of NO produced. Also shown in Figure 2 however, are other results obtained from a more detailed study of the effect of the mixedness.* From this latter data, it can be observed that $\bar{\Phi}_E^{**} = 0.8$ represents a low sensitivity operating condition, whereas at $\bar{\Phi}_E = 1.0$, large reductions in NO emissions are predicted as S_o increases. This variation in sensitivity may be explained by a careful consideration of the physical significance of S_o and the nature of the NO kinetics.

* These results were produced during the model development phase of the program and were described in Reference 9. The combustor geometry and operating conditions used were somewhat different than those used in the parametric analysis.

** $\bar{\Phi}_E$ represents the effective mass mean equivalence ratio in the primary zone when account is taken of the actual fraction of fuel burned in the zone (β). This parameter will be the one discussed in this section, rather than $\bar{\Phi}_p$, the mass mean equivalence ratio in the primary zone calculated on the assumption that all fuel is burned in the zone ($\beta = 1$), $\bar{\Phi}_E$ relates more directly to the nitric oxide formation characteristics. The two are simply related according to the equation $\bar{\Phi}_E = \beta \bar{\Phi}_p$.

Mixing in the primary zone is never complete at the time of combustion and consequently, elements burn with different equivalence ratios. The value of S_o represents this "spread" in equivalence ratios relative to the mass mean value, and $S_o = 0$ corresponds to the perfectly mixed case. Clearly, as S_o increases, the fraction of the gases in the primary zone that burn at the mass mean equivalence ratio decreases. If this mass mean value corresponds to that at which the nitric oxide formation rate is maximum, then the total nitric oxide formed will decrease. On the other hand, if the formation rate is very low at the mass mean value, then as mixing quality decreases (S_o increases), some elements of mass will burn to produce a higher rate of formation of nitric oxide and the emission levels will increase.

Computed results show that essentially all nitric oxide is formed within the range $0.75 < \bar{\phi}_E < 1.25$ for the combustor inlet conditions studied (see Table 1), and that the maximum formation rate for nitric oxide corresponds to an effective equivalence ratio between 0.95 and 1.0. The formation rates are found to decrease rapidly as $\bar{\phi}_E$ decreases or increases from the 0.95 value. It is not surprising, therefore, that the variation in sensitivity of NO emission levels to changes in primary zone mixing characteristics and the effective mass mean equivalence ratio are as shown in Figure 7. These results are highly significant, because they demonstrate that at mixedness values greater than 0.3, the NO emissions become almost independent of $\bar{\phi}_E$ for the range of $\bar{\phi}_E$ examined. Thus, large reductions in emissions will only occur with changes in primary zone equivalence ratio if the primary zone conditions are almost homogeneous. The results of this study clearly indicate the futility of attempting to predict nitric oxide emission levels unless some account be taken for the inhomogeneities that are present in all gas turbine combustors.

4.1.2 Primary Zone Fuel-Burning Fraction, β

The fraction of fuel burned in the primary zone, β , was computed from the primary zone combustion efficiency correlation in Figure 9. The nominal value for the combustor conditions studied is 0.8, and

values of β from 0.6 to 1.0 were used in the model sensitivity analysis. As shown in Figure 3a, variations in β have a strong effect on NO emissions, and a reversal in the β -sensitivity occurs in the range covered. The strong effect of β is attributable to its effect on mean primary zone temperature which, in turn, has a strong effect on the rates of NO formation. The reversal in the β -sensitivity curve was not explored in detail, but is suspected to result from increases in temperature and NO formation in the intermediate zone as β decreases.

4.1.3 Air Distribution Characteristics

The air distribution characteristics are essentially defined by specifying the function,

$$M_a = M_a(X)$$

where M_a is taken to be not the total air within the liner, but rather, the air that is fully mixed with the main combustor flow stream. The method used to calculate these distribution characteristics is based upon the mixing laws discussed in Section 3.2.2 and is described in Volume 3, Appendix XVI. Variation in mixing rates may have significant effects upon the levels of nitric oxide predicted by the model, and were evaluated as follows.

The computer results showed that, for the combustor conditions simulated, the nitric oxide formation process was essentially frozen in less than one radius distance downstream of the primary zone exit. This behavior reflects, of course, the drop in temperature in the combustor that occurs due to the addition of air at the liner wall. Over the one radius travel, the rate of air addition, dM_a/dX , was nearly constant, so the effect of mixing rate upon the nitric oxide emission predictions was determined by selecting two other higher values for dM_a/dX (the upper value approaching the instant-mixing assumption), and predicting new values for the emission levels. The results, shown in Figure 3b, indicate that the nitric oxide level predicted can vary by approximately 20 per cent below the value calculated by the mixing law.

4.1.4 Mixing Parameters of the Intermediate Zone

Mixing of the primary zone combustion products, the unburned fuel, and the additional air entering at the liner walls is assumed in the model to follow turbulent mixing laws and to be approximately proportional to the square root of the fractional distance traveled down the intermediate zone. The sensitivity of the model to this assumption was checked by varying the exponent to values above and below the value of one-half and the results are considered below.

The exponent A_1 represents the mixing characteristic for the combustion products and the results given in Figure 4 show the effect of changing its value about the nominal value of one-half. Nitric oxide levels are shown to increase from -10 to +10 per cent about this nominal value as A_1 increases from 0.2 to a high value of 1.0. An increase in the value of A_1 corresponds to a decrease in the mixing rate and, thus, a decrease in the rate of reduction of mass in the flow elements with near-stoichiometric mixture ratios. Hence, a reduced mixing rate is accompanied by an increase in total NO formation for a system where $\bar{\Phi}_E < 1.0$. The 20 per cent variation in NO actually represents a much larger fraction of the NO formed in the intermediate zone.

The exponent A_2 and coefficient A_3 together define the rate of burn-up of the fuel which leaves the primary zone unburned (see Fig 4). These parameters effectively determine the average axial temperature profile in the early stages of the intermediate zone in a manner which is also related to the local rate of addition of air at the liner walls. For the nominal case, $\bar{\Phi}_E = 0.8$ and $\beta = 0.8$, an increase in the rate of fuel burning (A_2 smaller, A_3 larger) results in the maintaining of a high temperature condition in the early stages of the zone. As shown in Figure 4, however, the NO emission rate for this case does not vary greatly-- only from -10 to +20 per cent of the nominal value. However, as with the effect of A_1 , this 30 per cent variation of the total NO emission rate represents a large fraction of the NO formed in the intermediate zone.

The final mixing parameter C_N , introduced for this zone defines the rate of intermixing between the elements of various equivalence

ratios and nitric oxide concentrations. It specifies the amount of mass that leaves an element due to intermixing during an incremental step down the zone to the total mass flow rate through the element (see Volume 3, Section 2). The greater the value of C_N , the more vigorous the mixing between the elements. Its main effect is to modify the nitric oxide concentration and so influence the local formation rate. The net result of all mixing is to change element concentrations towards the average value, thus certain elements will increase in concentration and others reduce in concentration. An increase in concentration will reduce the nitric oxide formation rate and vice versa. It is not surprising therefore, to find that the model predicts that nitric oxide emissions are also quite insensitive to the value given this parameter (see Fig 4), as the effects are self-compensating.

4.1.5 Kinetic Rate Data

The results obtained by using the alternative sources of reaction rate data described previously, are summarized in Table 3. Nitric oxide emission levels can be observed to vary by a factor greater than two, depending upon the set of data used. This "parameter" is shown to exert the greatest influence upon the model predictions. The results also show that reactions 4, 5, and 6 exert a negligible influence upon the results for all cases tested.

4.1.6 Conclusions

As stated earlier, the purpose of the model sensitivity analysis was to evaluate the sensitivity of the model predictions to variations in model parameters (as distinguished from design parameters). With this purpose in mind, the following conclusions can be drawn from the model sensitivity analysis for the case tested:

- a. The degree of mixedness, S_O , and the fuel-burned fraction, β , assigned to the primary zone have significant effects upon the predicted nitric oxide emissions.

- b. Mixing rates in the intermediate zone affect the amount of NO formed in this zone to a substantial degree. This effect is most pronounced with the rates of mixing of elements of differing fuel fraction; and mixing of unburned fuel and secondary air. For the combustor design and operating conditions investigated, most NO is formed in the primary zone. Therefore, intermediate zone mixing effects are considered to be of secondary importance with respect to total NO emission rate.
- c. The predicted NO emission rate is very sensitive to the reaction rate constants used in the NO formation model. It is shown that, depending on the data selected, predicted nitric oxide levels can vary by a factor of greater than two. Some variation in predicted NO emissions was expected since a wide selection of rate constants was used. However, as indicated in Table 3, the greatest discrepancy occurs between the two sets of constants which were considered to be most reliable for this application (ICODE's 1 and 2).

4.2 DESIGN SENSITIVITY ANALYSES

Conditions simulated in the design sensitivity analysis were those experienced by a combustor when operating under conditions corresponding to the idle, take-off, cruise, and approach modes of a modern airliner. The three variables considered to be the most significant and studied in detail were as follows:

- a. The mean residence time in the primary zone, $\bar{\tau}_p$.
- b. The mean equivalence ratio in the primary zone, $\bar{\phi}_p$.
- c. The engine pressure ratio, EPR.

Throughout this analysis, the condition was imposed that the thrust level be constant for each operating mode despite changes in these prime variables.

4.2.1 Mean Primary Zone Residence Time

if all conditions are constant, then the primary zone residence time is directly proportional to the volume of the primary zone, V_p .

The effect of residence time upon NO emission characteristics was determined at each of the four operating modes simply by assuming that:

$$V_p = 0.7 \times \text{Nominal Value}$$

$$V_p = 1.3 \times \text{Nominal Value}$$

The results are given in Figure 5. All show a strikingly similar variation in nitric oxide emission levels with the level increasing by approximately 1.2 lbs NO/1000 lbs of fuel for all modes except the idle mode.

It is interesting to observe that the nitric oxide emissions do not increase in direct proportion to the primary-zone residence time particularly at the operating conditions which correspond to the high levels of emission. This result can be attributed to the fact that, in the combustor studied, a significant fraction of the total NO formed is found in the intermediate zone. In the analysis, the intermediate zone conditions were not changed so that the NO fraction formed there also did not change. The NO fraction formed in the primary zone varies almost in direct proportion to primary zone residence time, $\bar{\tau}_p$. Thus, the total NO emission level does not vary in direct proportion to $\bar{\tau}_p$.

4.2.2 Mean Primary Zone Equivalence Ratio

A change in the primary zone equivalence ratio will change the residence time if the primary zone volume is kept constant and will also produce a change in the over-all equivalence ratio (hence, thrust level) unless the airflow characteristics are modified. For the operating conditions simulated in this study, residence time was specified as constant for each mode and equal to the nominal value. The constant thrust condition imposed at the onset of the calculations was assumed to be satisfied if the total mass flow rates of the fuel and air were maintained constant. For richer primary zones, therefore, less air was assumed to enter the primary zone, and the air distribution characteristics were modified such that the total airflow at the exit remained constant for each mode. The following simple relationship was used:

$$M_a = M_{a_{\text{nominal}}} \left[i - (1 - 1/R) \left(\frac{X_E - X}{X_E} \right) \right]$$

where M_a = total airflow rate

R = the ratio of the tested equivalence ratio to the nominal value

X = the axial position corresponding to the value of M_a

X_E = the end of the combustor.

This method was used to determine the effect that the primary zone equivalence ratio has upon NO emission levels at the values of the ratio other than the nominal one. These corresponded to

$$\bar{\Phi}_p = (\bar{\Phi}_p)_{\text{nom}} \times 0.8$$

$$\bar{\Phi}_p = (\bar{\Phi}_p)_{\text{nom}} \times 1.2$$

and all four operating modes were tested. The results are shown in Figure 6.

As could be anticipated, in those cases in which the change results in $\bar{\Phi}_p$ values away from the stoichiometric condition, NO emissions reduce, whereas when $\bar{\Phi}_p$ moves toward this condition, the NO emissions increase. This effect is most significant for the cruise and approach operating modes, where for the test cases, NO emissions are shown to increase by a factor of three over the range of primary zone equivalence ratios considered. Special note must be made, however, of the influence of the assumed value of the primary zone mixedness parameter, S_o . The nominal value used in these calculations corresponded to a value of 0.2 (Table 1). The sensitivity of these results to the value of S_o as shown in Figure 2.

4.2.3 Pressure Ratio

For the nominal test case, the engine pressure ratio was equal to 16.7:1 at the take-off mode. Operating conditions were simulated for the

$$\text{EPR (take-off)} = 12:1 \text{ and}$$

$$\text{EPR (take-off)} = 25:1$$

and their nitric oxide emissions were predicted at all four modes of aircraft operation.

Pressure levels within the combustor at off-design conditions were assumed to be proportional to the EPR and were computed based upon the data for the nominal case. Combustor inlet temperatures were determined from data supplied in Hodge (Fig 104, Ref 12).

In order to maintain operating thrust, primary zone mean residence time and equivalence ratio all constant, and at the same time vary the EPR, new combustor dimensions had to be defined for the cases of EPR = 12:1 and 25:1. The method used assumed the following:

- a. That the combustors operated with the same reference velocity, v_r , as for the nominal combustor, where:

$$v_r = M / \rho A \text{ and}$$

M = total airflow rate

ρ = air density at inlet

A = cross-sectional area of liner

If, as an approximation, the density is assumed to be proportional to pressure, P , and if the total mass flow is fixed, then this criterion implies that the product PA is constant. The value of the product was known for the nominal combustor, so the values of the liner area could be computed for the two combustors operating at other pressure levels.

- b. That the volumes of the primary zone of the new combustors were such that the residence times were equal to that of the nominal combustor. This, of course, is an artificial constraint upon the combustor dimensions, but it was applied so that the effect of pressure ratio upon nitric oxide emissions could be evaluated in isolation from the other prime variables. Checks were made to ensure that the combustors sized by this approach would have an adequate combustion efficiency by methods detailed in Reference 4. The methods showed that for the EPR values tested, all three combustors would perform with the same efficiency.

The effect of EPR upon nitric oxide emissions rests not so much upon the absolute pressure level that results, as upon the fact that the inlet temperature to the combustor and flame temperature increase

with the EPR. At high inlet temperatures of, say, greater than 800 deg K, changes of the order of 50 deg K have significant effects upon the predicted nitric oxide emission level. The results given in Figure 7 show that the engine compressor pressure ratio has a far greater effect upon emission level of nitric oxide than all other variables studied; that is to say that the inlet temperature to the combustor tends to exert the greater influence upon emission characteristics. This applies for all operating modes (except idle), and it is predicted that as the EPR progresses from 12 to 16.7 (the nominal value) and to 25, emission levels at all modes increase approximately in the ratios 1:2:4.5. In practice, this dependence is not so large, as other factors must be considered when the value of EPR is changed and a discussion of these factors follows.

4.2.4 Pressure Ratio Effects, Specific Fuel Consumption, Specific Thrust and Emissions

A change in EPR will result in a change in both the thermodynamic efficiency of the engine and a change in the specific thrust, i.e., the lbs thrust per lb of air per sec that flows through the engine. In general, the specific thrust is relatively insensitive to EPR at the conditions tested above (i.e., a fixed exit temperature from the combustor), and upon this observation is based the assumption stated earlier that constant thrust corresponds to a fixed mass flow rate. But clearly, any improvement in the thermodynamic efficiency must result in less fuel being burned per unit time to achieve the same thrust level, and hence less nitric oxide being generated. Some credit should be allocated to the higher EPR engines for this fact. For the pressure range and operating conditions tested above, however, this credit is within ± 0.05 of the nominal value and can therefore be ignored.

The considerable improvement in engine performance that can be obtained by resorting to higher EPR values is only realized if the maximum cycle temperature, \bar{T}_m (that is, the mean temperature at the exit of the combustor), is also increased. Such a change does further

improve specific fuel consumption, but has a much greater effect upon the specific thrust as is shown below:

\bar{T}_m Deg K	Specific Thrust Ratio	$\bar{\phi}$ Over-All (Approx)
1273	1.0	0.17
1473	1.25	0.27
1673	1.45	0.37
1873	1.60	0.47

where specific thrust ratio is the thrust at \bar{T}_m divided by that at \bar{T}_m equal to 1273 deg K, which corresponds approximately with the nominal operating point. These results indicate that the same thrust level can be delivered for a lower mass flow rate of air. It is interesting to note also that the required over-all fuel-to-air ratio never exceeds one half of the stoichiometric requirement. As all nitric oxide formation reactions are essentially frozen at ratios less than six tenths the stoichiometric value, this implies that, to a first approximation, the nitric oxide concentrations at the combustor exit need not be changed at all by the increase in the maximum cycle temperature. Hence some credit is due to the combustor with the higher specific thrust as the total nitric oxide emitted per unit time is decreased. The maximum cycle temperature that is currently in common practice corresponds to a specific thrust ratio of about 1.5. If this correction is applied to the emission ratios given at the end of the previous section, then the predicted nitric oxide emission rates are approximately increased by 1:2:3 as the EPR progresses from 12 to 16.7 to 25.

4.2.5 Experimental Data

In Figure 8, measured NOx emission data are plotted in the same manner as the theoretical predictions in Figure 7. The data have been taken from Reference 13, and each point in the figure is an average measurement for several different engines of the same model or family. A comparison of Figures 7 and 8 indicates that the effects of engine

pressure ratio on NO emission rate as predicted by the model are substantially confirmed by the measured data. The main discrepancy occurs at the idle condition where the model predicts essentially zero emissions.

4.2.6 Conclusions

The following conclusions can be made from the results obtained in the design sensitivity analysis:

- a. The model does predict nitric oxide emissions which are in accord with measured values.
- b. The dominating influence upon emissions level is the engine pressure ratio, but large reductions in nitric oxide emissions appear to be feasible for any given operating pressure by modifying the primary zone operating conditions.

5. THE EXPERIMENTAL PROGRAM

5.1 TEST OBJECTIVES

The results described in the previous sections indicate that, although the present computer model does predict nitric oxide emission levels that are in reasonable accord with experimental values, there is some question concerning the accuracy in calculation, or assumed value, of some of the parameters used in the computation. The main objective of the experimental test program was to determine the nitric oxide emission levels from some gas turbine combustors under closely controlled test conditions so that the relevance of these questions could be resolved and confidence in the model increased.

At the same time it was planned to collect emission levels of other pollutant species as they varied with the test operating conditions and so define the emission characteristics for these species. This data could then be used to indicate the effect that nitric-oxide reducing changes in combustor design might have upon the levels of these emissions.

5.2 TEST PLAN

It is concluded from the foregoing analysis that for a fixed combustor and operating condition the following parameters are the most significant in terms of their effect upon nitric oxide emission levels:

- a. The fuel-burning fraction in the primary zone, β .
- b. The effect of imperfect mixing in the primary zone, S_o .
- c. The air distribution characteristics, dM_a/dx .
- d. The kinetic rate constants.

Of these four parameters, only three are variables as there can be only one accurate set of kinetic data. Due to the present uncertainty in the relative accuracy of the data available in the literature, however, the correct one must be selected based upon the experimental results. Clearly, the test plan must aim to produce conditions for

which significant variations in the three variables occur. The test plan adopted, therefore, was to test two combustors developed by different design criteria (i.e., different manufacturers) and the following tests were made.

5.2.1 Test Series 1 - Combustor A

Exhaust concentrations only were measured in the first test series. Concentrations of nitric oxide, carbon monoxide, and unburned hydrocarbons were recorded as the operating conditions of the combustor were systematically varied to cover the following ranges of operating conditions; where P = inlet pressure in psia, T = inlet temperature in deg K, AFR = air-fuel ratio.

	P	T	AFR	Comments
a.	85	600	70	Residence time varied for same test conditions
	85	700	50 to 140	
	85	800	60	
b.	115	600	55 to 140	Residence time at design values
	115	700	50 to 120	
	115	850	50 to 90	
c.	40	400	40 to 80	Residence time at design value

5.2.2 Test Series 2 - Combustor B

In the second series, measurements were taken both at the exit plane of the combustor and at axial stations within the combustor at the following conditions:

	P	T	AFR	Comments
a.	85	600	60 to 130	Exhaust concentrations only, residence time at design value
	85	700	55 to 130	
	85	800	65 to 115	
b.	70	600	88	Internal probing
Measurements were taken, within the combustor of radial profiles of nitric oxide, carbon monoxide, temperature, and pressure at two axial stations located approximately 0.5 diameters and 1.0 diameters downstream of the primary zone exit.				

5.3 EXPERIMENTAL EQUIPMENT

5.3.1 The Combustor Testing Facility

The experimental test arrangement employed is shown schematically in Figure 10 and photographically in Figure 11. It comprised an air supply, an air preheater in the form of a pebble-bed heat exchanger, an air mixer, a water-cooled tailpipe, and a high temperature regulating valve. Control was effected remotely in a test room located about 15 ft from the combustor (see Fig 12). Airflow rates for most tests were within the range of 4 to 7 lbs per second and combustor inlet temperature was adjusted by diverting different percentages of air through the pebble-bed. Temperature traverse quality at the exit of the mixer was within ± 15 deg K of the nominal value, and the combustor entrance was located just downstream of the mixer exit. Casings were manufactured to the dimensions experienced by the combustors during in-flight conditions to ensure that the air distribution characteristics in operation during testing matched design conditions.

5.3.2 Sampling Methods

Two sampling methods were employed. The first system, shown in detail in Figure 13, collected exhaust gases from the exit plane of the combustor through a diametral probe. The probe contained nine holes of 0.040 inches in diameter spaced to give equal area sampling. The probe itself was water-cooled, but the 20 ft of sample line from the probe to the instrumentation room was heated to about 470 deg K to prevent condensation of the hydrocarbons. After hydrocarbon sampling, the gases passed through a series of coolers, traps, and filters to remove the water and the carbon.

The other probe system employed was used for probing the interior of the second combustor tested. A stainless-steel probe was water-cooled with a high pressure water supply system and entered the combustor normal to the direction of the gas flow. The probe tip consisted of a short length of right-angled silica tube which was inserted well into the metal body of the probe. Silica was used to limit the possibility

of obtaining erroneous readings for nitric oxide concentration levels if the sampling region probed were to be fuel-rich (see Ref 14). The exit of the probe was then connected to the sample-conditioning train used for the exhaust probe (see Fig 13).

5.3.3 Instrumentation

Measurements of airflow rate, pressure, temperature, and velocity were all made using conventional instrumentation techniques. Pollutant specie concentrations were measured as follows:

- a. Nitric Oxide. Four techniques were used for measuring nitric oxide concentrations but only one was used consistently throughout the course of the test program. This was a nondispersive infrared method which employed a Grubb Parsons SB2 instrument with a 20 cm cell and a specially-developed, integral, filter system to minimize the response to water and hydrocarbons. It was found, however, that the measurements taken using this method were invalidated due to any water in the sampled gas. The problem was eliminated by use of an additional drying tube packed with calcium sulphate. The system sensitivity to any unburned hydrocarbons in the sample gas was always suspect until it was checked against a Thermo Electron chemiluminescent analyzer. This analyzer was employed continuously over the last one-third of the test program and showed that excellent agreement could be obtained between the two techniques for all nitric oxide levels greater than about 15 ppmV nitric oxide. These emission levels corresponded to simulated idle conditions in the engine which also had very high levels of unburned hydrocarbons (greater than 100 ppmV). Even under these conditions, the chemiluminescent analyzer gave readings which were no lower than 10 ppmV below the NDIR readings. In operation, both methods were calibrated with pre-calibrated gases of 200 and 100 ppmV NO in nitrogen and linearity was checked by controlled dilution of these gases. Linearity was found to be better than required in both cases (± 2 ppmV NO).

Measurements were also using the standard Saltzman and Phenol Disulphonic Acid techniques but these were restricted mostly to test conditions corresponding to the idle mode and before the chemiluminescent instrument became available for use.

- b. Carbon Monoxide. Carbon monoxide was also measured using the NDIR method by means of a Grubb Parsons SBI analyzer. This analyzer had a 30 cm cell with a carbon dioxide filter attached.
- c. Unburned Hydrocarbons. A Perkin-Elmer FII flame ionization gas chromatograph was used to measure unburned hydrocarbons and the instrument was calibrated with hexane.

5.4 SUMMARY OF RESULTS

A summary of all test results obtained is given in Tables 4 and 5 and these will be presented in graphical form in the next section where they are compared with the model predictions.

6. COMPARISON BETWEEN MODEL PREDICTIONS AND EXPERIMENTAL RESULTS

6.1 MODEL INPUT DATA

The required input data for the model were first determined for each of the two combustors tested experimentally and according to the principles described in Sections 3 and 4.

6.1.1 Combustor Characteristics

The greater part of this calculation involved the determination of the air distribution characteristics throughout each combustor and, in both cases, the distribution characteristics were based upon measured data supplied by the manufacturers. These data specified the percentage of the total air supplied to the combustor that entered at each hole in the combustor liner, and the objective of the calculations was to take account of the finite distance lag that must exist before the entering air gets entrained by the combustion products formed in the upstream sections of the combustor. The method used is detailed in Volume 3, Appendix XVI, and the results are shown graphically in Figure 14. The combustor dimensions are given in the table below, and, like the air distribution characteristics, the values were considered invariant with combustor operating conditions:

Combustor Geometry

	<u>Combustor</u>	
	<u>A</u>	<u>B</u>
Volume of Primary Zone (V_p) in ³	38.0	88.5
Length of Intermediate Zone (X_L) in	7.0	7.0
Length of Intermediate and Dilution Zone (X_{END}) in	14.0	12.5
Combustor Radius (R) in	2.63	3.25

6.1.2 Combustor Operating Conditions

Five variables are sufficient to describe the combustor operating conditions:

- a. T - Inlet temperature
- b. P - Operating pressure
- c. $\bar{\phi}_p$ - Mass mean equivalence ratio in the primary zone (for $\beta = 1$)
- d. β - Fraction of fuel entering the primary zone which burns in the zone
- e. M_{ax} - The total mass airflow rate into the combustor.

Conditions a, b, c, and e were made to match the conditions tested experimentally and the value of β was calculated from the correlation given in Reference 15 and also shown for convenience in Figure 9. The value of the primary zone equivalence ratio is simply related to the over-all air-fuel ratio in a manner dictated by the fraction of air that enters the primary zone, and for the two combustors tested, this relationship is shown in Figure 15. Also shown in this figure is the effective primary zone equivalence ratio that exists when account is taken of the primary zone fuel-burning fraction, β , for one particular operating pressure. It can be observed from this figure that the operating conditions in the primary zones vary significantly for the two combustors tested experimentally. Combustor A is calculated always to operate at conditions below the stoichiometric condition, whereas Combustor B is shown to operate fuel-rich for air-fuel ratios less than 65.

6.1.3 Primary Zone Mixing Parameter

This parameter, S_o , describes the degree of mixedness in the primary zone (see Section 3.2.1). Practically, this parameter can have a range of values from perhaps near zero, corresponding to near perfect mixing, to about one, very poor mixing, and for the purpose of comparing the model predictions with the experimental results, it was considered to be a matching parameter. That is to say, its prescribed value was varied parametrically and the effects of so doing observed in the predicted results and compared with the experimental results.

6.1.4 Kinetic Constants

The reaction scheme for nitric oxide formation rate described earlier has six intermediate steps, each with the general form,

$$k = AT^n \exp(-E/RT)$$

where k is the reaction rate constant. Each step, of course, has its own characteristic values for A , n , and E and these must be specified in the input data. Four sets of such data are presented in Table 2 and are referenced as ICODE = 1 to 4.

At the start of this study, the first set of data was thought to be the most useful as it had been successfully used to correlate piston engine nitric oxide emissions (Ref 10). The second set of data (ICODE = 2) was considered the most accurate as it is the product of an extensive study of all the available nitric oxide kinetic data (Ref 11). Results obtained with the latter data predicted higher values of nitric oxide emissions than the former and this set of data has been used to obtain the predicted results presented in this section. Results obtained with the first set of data were found not to match the measured results as well as with the second set.

Measured Value	First NO Predictions* Kinetic Data (ICODE)	
	1	2
ppmV	ppmV	ppmV
132	70	145

Some typical results are shown in the above table. It is recommended that the data referenced by the code ICODE = 2 be used with the model presented in this report.

* See Table 2. ICODE = 1 corresponds to data used to match results for piston engine and ICODE = 2 corresponds to the data selected in a comprehensive survey of the data as being the most reliable (see Ref 11).

6.2 MODEL VERIFICATION

The two combustors employed in the test program were operated at a common test condition, where $P = 85$ psia, $T = 700$ deg K, and AFR varied from 50 to 150, and were found to exhibit significantly different nitric oxide emission characteristics. At the lowest AFR value their emission levels were comparable, but as the AFR increased, the emissions from Combustor A decreased much more rapidly. This was considered a convenient point to start the comparisons between the model predictions and the measured data, as it would clearly provide a good test for the model.

The first calculations were made, therefore, for this test condition and the range of the mixedness parameter S_o was varied between 0.3 and 0.7 for both cases. The results, compared in Figure 16, show a good agreement with experimental data particularly for Combustor B when $S_o = 0.7$ where the predictions are approximately only 20 per cent high over the whole band of AFR tested. For Combustor A, the agreement is not so successful, particularly at the one point where the air-fuel ratio is approximately 140. An acceptable level of agreement is obtained for the case of $S_o = 0.7$, but the predicted gradient of nitric oxide emissions with AFR is much lower than measured, whereas at $S_o = 0.3$, the gradient is matched almost perfectly over the range $50 < \text{AFR} < 90$, but predicted values are lower than the measured values. Before discussing reasons for these discrepancies, it is worthwhile to compare the calculated results for these two cases in more detail.

In Sections 6.1.1 and 6.1.2 it was shown that the two combustors under study have significantly different design characteristics. Combustor A has a small primary zone with a high fuel-load factor, hence low efficiency, and operates very lean compared to Combustor B, when operated at the same AFR value. This latter combustor burns relatively efficiently in the primary zone, but with a richer combustion mixture. Calculated predictions of the internal details of mass average temperature, equivalence ratio, residence times, and nitric oxide levels are shown in Figure 17 for AFR values of about 60.

The comparisons are striking. Combustor A is predicted to have a top mass average temperature approximately 275 deg K lower than Combustor B and also a significantly shorter residence time to the time of freezing of the nitric oxide formation process, (4 msec versus 8 msec). Another difference predicted by the model is that for Combustor A nearly 60 per cent of the total NO emitted at the exhaust is formed in the primary zone, whereas for Combustor B, only 30 per cent has this zone as its origin. This of course, reflects the difference in operating equivalence ratio conditions.

6.2.1 Comparison with Combustor A

The disparity between the predicted and measured values obtained for Combustor A and shown in Figure 16 can be improved. It appears that a value of the mixedness parameter S_0 of 0.3 is preferable as it matches the slope of the measured points very well. The observation presented above, that for this combustor the primary zone is the active center for NO production, suggests that a better agreement could be obtained if the primary zone fuel-burning fraction, β , were greater than that indicated by the combustion efficiency correlation. As noted previously, the use of this correlation tends to "under-predict" β . Therefore, more computer runs were conducted, leaving all conditions constant except for an increase in β to a value of 1.15 η_{cp} . Results calculated on this basis show a marked improvement (see Fig 18), and now become quite acceptable for AFR values less than about 90. At values greater than this number, the mean effective equivalence ratio in the primary zone soon drops lower than 0.5 (see Fig 15) and due to the limit imposed in the model that $\phi_{max} = 2 \bar{\phi}$ (see Volume 3, Section 2), a region is soon reached where no nitric oxide will be predicted (as it is necessary for some mass to have ϕ value greater than about 0.85 for NO to be formed). Practically, combustion becomes difficult to sustain at these low values in equivalence ratio and the difficulty is overcome by the use of a pilot flame which operates from its own fuel supply system. It is clear, therefore, that in the experimental tests, most of the nitric oxide formed under these conditions will

have its origin at the pilot flame as the pilot region is normally designed to operate around stoichiometric at these high AFR values for they correspond to the idle operating conditions in aircraft gas turbine engines. The model clearly has its limitations for such test cases, but it is a problem that can readily be modified by accounting for the pilot and main flows separately. As the nitric oxide levels under discussion are only about 20 ppmV, it is not considered to be a serious limitation at this stage.

Further calculations were made to compare predictions with the experimental results obtained at higher pressure, $P = 120$ psia, and again the mixedness parameter was set equal to 0.3 and the fuel-burning fraction set equal to $1.15 \eta_{CP}$. The results of these comparisons, shown in Figure 19, indicate fair agreement between measured and predicted emission rates at AFR values less than 90. However, the model appears to overemphasize the effect of inlet air temperature so that agreement is not achieved simultaneously at all temperature levels. It is expected that more favorable agreement could be achieved through further comparisons with variations in other model parameters.

6.2.2 Comparison with Combustor B

- a. Exhaust Emission Data. Figure 16 shows a good agreement between predicted and measured nitric oxide emissions for Combustor B when the primary zone mixedness is assumed to equal 0.7. As for the case of Combustor A, it too can be improved, but for this combustor, as most nitric oxide is formed in the intermediate zone, an improved agreement can best be obtained by modifying the air distribution characteristics. The limit to this modification clearly corresponds to the assumption that the air entering the casing holes mixes instantaneously with the upstream products. This is not realistic, but does serve to show the sensitivity of the predictions to the method of calculation. Therefore, calculations were made for the calculated distribution and the limit this distribution can attain, and the results are shown in Figure 20.

Two observations can be made about these results:

- i. A much better agreement is obtained at the high AFR test points than was the case for the previous combustor. Figure 15 shows that for Combustor B at AFR of 120, close to the highest value tested experimentally, primary zone effective equivalence ratio is as high as 0.6 and thus it is not surprising that the model limitations described in 6.2.1 do not apply to these test conditions.
 - ii. Good agreement between predicted and measured results is obtained at one inlet temperature condition (700 deg K), but agreement is less satisfactory at other temperatures. A different variation in model parameters is required to reduce the predicted sensitivity to inlet temperature.
- b. Internal Probe Test Results. The objective of the internal probe tests was to attempt to determine the mass average concentrations of nitric oxide and carbon monoxide as they varied with axial position. The basic data are given in Tables 5b and 5c and are summarized in the table below, where total pollutant mass flows are given to be equal to the product of concentration and local product flow rates:

X in	CO conc. ppmV	<u>Measured Data</u>		NO total ppmV x M_{ax}	<u>Predicted Data</u> [*]	
		CO total ppmV x M_{ax}	NO conc. ppmV		NO conc. ppmV	NO total ppmV x M_{ax}
0.0	--	--	--	--	195	268
3.0	3000+	4800+	210	335	182	290
7.0	425	1280	120	360	96	290
Exit	120	710	58	345	49	290

Concentration values change with axial position due to both chemical reaction and dilution by the additional air which enters the combustor liner. If there is no chemical reaction, then the total mass flow rate of the species concerned should remain constant along the

* Predicted data indicate that the nitric oxide reaction rate is essentially zero at X = 2.9 inches.

combustor length. The predicted nitric oxide emission data indicate that this occurs within the first 3 inches of travel from the primary zone. The measured data for nitric oxide levels also indicate the same behavior if one makes allowances for the errors involved in the determination of the mass average concentration. This is clearly not the case for the carbon monoxide oxidation reaction as the experimental results show that there is at least a sevenfold reduction in total carbon monoxide levels as the combustion products travel from the 3-inch station to the exit.

6.2.3 Comparison at Low Power (Idling) Conditions

Experimental tests were also carried out on both combustors at operating conditions which correspond to those encountered in the engine idle mode. It is known that significant amounts of nitrogen dioxide (NO_2) can be present in the sampled exhaust gases under these conditions so tests were made using both wet-chemistry techniques (phenol-disulphonic-acid method and Saltzman) and the chemiluminescent analyzer (see Section 5.3.3) for the quantity of NO_2 present. The results are given in Figure 21 and are also compared with predictions made by the model.

The following observations can be made from this figure:

- a. Total NO_x levels as measured by the Saltzman technique are significantly higher than the nitric oxide levels measured by either the NDIR or chemiluminescent techniques.
- b. Total NO_x as measured by Saltzman and the chemiluminescent analyzer which incorporated an NO_2 to NO converter do not agree. The converter efficiency of the analyzer was checked by passing known concentrations of NO_2 through the converter and found to vary between 30 and 60 per cent. The discrepancy, therefore, appears to be due to the difficulty in conversion of the NO_2 present.
- c. Nitric oxide levels measured by the NDIR technique are higher than those measured with the chemiluminescent

analyzer, particularly at the high values of AFR. The measurements made by the two, however, tend to come closer as the AFR reduces, that is, as the combustor temperatures increase. No noticeable discrepancy occurs when the combustors operate at an inlet temperature higher than the 400 deg K that applies here. The discrepancy is thought to be due to the high level of unburned hydrocarbons (greater than 100 ppmV as methane) that exist in the combustor exhaust at this condition as it is known that the NDIR technique does respond to hydrocarbons.

- d. The model predictions for nitric oxide emissions agree satisfactorily with the nitric oxide measurements made by the chemiluminescent method.

6.3 CONCLUSIONS

The following conclusions are made based upon the results presented in this section:

- a. The model presented in Section 3 adequately predicts nitric oxide emission characteristics at high-power regions for the two combustors tested, if one ignores operating conditions which produce nitric oxide emissions of less than 30 ppmV.
- b. Improved accuracy in prediction of nitric oxide emissions will depend as much upon the accuracy of determination of the primary zone mixedness and fuel-burning fraction, the air distribution characteristics within the combustor liner, and the kinetic data as upon improvements to the proposed flow models.
- c. The model requires refinement if it is to satisfactorily predict nitric oxide emissions at low power level conditions (basically defined by T being less than 500 deg K and primary zone equivalence ratio dropping below 0.5). Consideration must also be given to nitrogen dioxide (NO_2) emissions which constitute a substantial fraction of total NO_x emissions at low power levels (Ref 13).

7. DESIGN CRITERIA

7.1 THE COMBUSTOR DESIGN PROBLEM

7.1.1 Performance Requirements

In the design of a gas turbine combustion chamber, several distinct performance requirements must be met. These requirements can be classified as follows:

Aerodynamic Performance

- a. Total pressure loss.
- b. Outlet temperature profile.
- c. Wall temperature distribution.

Combustion Performance

- a. Combustion efficiency.
- b. Combustion stability.
- c. Ignitability.
- d. CO and HC emissions.
- e. Particulate emissions and smoke.
- f. NOx emissions.

Mechanical Performance

- a. Weight.
- b. Durability.
- c. Cost.

This method of classification groups requirements which are most closely related. Aerodynamic performance requirements are primarily related to the airflow and velocity distributions in the combustor. Combustion performance requirements are related to the detailed designs of the primary and intermediate zones and the fuel injection systems. Mechanical performance requirements are related to the mechanical design techniques and materials used in the combustor. These performance groups are, of course, highly interrelated.

In meeting the NOx emission control requirement, we must be concerned with its interactions with all the other combustion

requirements and we find that certain aerodynamic requirements are indirectly affected by NOx emission control techniques. Therefore, we are concerned with those parameters which represent both the combustion and aerodynamic performance of the combustion chamber when we design for controlled NOx emissions. Mechanical performance requirements, however, generally are not significantly affected by combustor design modifications considered for NOx emission control and, therefore, will not be included in this discussion.

7.1.2 Design Procedures

The complete combustor design procedure is lengthy and complex. An outline of the procedure is presented here to identify the principal design parameters which the designer has under his control. This discussion applies to combustors of either can or annular configuration. For convenience, terminology applicable to can configurations will be used.

In designing a combustor, the following categories of independent design variables are involved:

- a. Combustor diameter.
- b. Combustor length.
- c. Fuel nozzle characteristics.
- d. Effective air hole area.
- e. Configuration and location of air holes.

The ultimate objective of the design process is the specification of these quantities. When these design variables have been specified, the "aerodynamic" design of the combustor is essentially complete, and the mechanical design process can be initiated.

To develop a set of design variables which will result in satisfactory combustor performance, the designer actually works with a set of intermediate design parameters which are more closely related to the physical processes occurring in the combustor. Different combustor designers work with different sets of intermediate parameters, but the set listed below is representative of current practice:

- a. Pressure loss factor.
- b. Combustion loading parameter.
- c. Combustion zone fuel-air ratio.
- d. Fuel nozzle performance factors.
- e. Combustion zone length (or volume).
- f. Dilution zone length (or volume).

The pressure loss factor is essentially a combustor drag coefficient and is defined as follows:

$$\frac{\Delta P}{q_{ref}} = \frac{\Delta P}{P} \left[\frac{U_{ref}^2}{2 R T_{in}} \right]^{-1}$$

where ΔP = pressure drop across the combustor

$$q_{ref} = \frac{\rho_{in} U_{ref}^2}{2}$$

$$U_{ref} = \frac{M}{\rho_{in} A_{ref}}$$

A_{ref} = maximum combustor casing cross-sectional area

$$\frac{\Delta P}{P_{in}} = \text{pressure loss fraction}$$

The pressure loss factor usually is assigned a value which has been shown from experience to be consistent with satisfactory combustor aerodynamic performance. When the value of this factor is specified, the combustor diameter and pressure loss fraction are uniquely related for each operating condition.

The combustion loading parameter indicates directly or indirectly the heat release rate occurring in the combustion zone. Various forms of this parameter have been defined (Ref 15). The form used by NREC was developed at Rolls-Royce Ltd. (Ref 16) and is defined as follows:

$$\Theta = \frac{\dot{P}_{in}^{1.75} A_{ref} D_{ref}^{0.75}}{M} \exp(T_{in}/b)$$

where D_{ref} = maximum combustor casing diameter

b = constant (function of combustor fuel-air ratio).

The combustion loading parameter is assigned a value consistent with satisfactory combustion performance, including combustion stability and efficiency, and ignitability at maximum altitude. It should be noted that both the pressure loss factor and combustion loading parameter are related to combustor diameter so that the combustor must be sized to meet both criteria.

Two fuel-air ratios characterize the combustion zone-- that in the primary zone and that in the intermediate zone. Both quantities must be specified in order to fix the combustor airflow distribution.

The performance of conventional fuel nozzles can be specified directly by means of spray characteristics-- spray angle, velocity, and droplet size distribution. However, with the advent of carbureting fuel injection systems, these characteristics no longer suffice since the fuel introduction process is affected by the design of the combustor as well as the nozzle. A requirement exists for a fuel injection performance parameter, such as the primary zone mixedness parameter (S_o) defined in this program, which indicates the distribution of fuel in the airflow and can be related to combustor and nozzle design variables. At present, the S_o parameter meets the first requirement, but not the second. Thus, S_o cannot be specified quantitatively at present. However, minimizing S_o is considered to be an effective qualitative criterion for meeting certain combustion performance requirements-- notably smoke and NOx emission control.

The combustion zone length is the sum of the primary zone and intermediate zone lengths. The former is essentially fixed by the combustor diameter since the recirculatory flow pattern of the primary zone requires a "square" profile. That is, the primary zone length must be of the same order as the combustor radius. However, the designer is free to specify the length of the intermediate zone consistent with the attainment of satisfactory combustion efficiency, and CO and HC emission rates.

The dilution zone length mainly affects the outlet temperature profile. Thus, this factor is primarily related to combustor aerodynamic performance rather than combustion performance.

By specifying the values of these intermediate parameters, the designer establishes the gross characteristics of the combustor and most of the factors which determine aerodynamic and combustion performance. The remaining tasks consist of detailed design of flow passages, and specification of location and configuration of cooling air passages.

The performance and design parameters have been defined here as they are encountered in the development of a new combustor. In this development problem which we refer to as the new combustor development procedure, the performance factors are specified a priori as well as the combustor operating conditions. The design parameters then are specified so that the performance requirements will be achieved.

A somewhat different procedure is required when an existing combustor is to be modified. In this development problem, which we refer to as the modified combustor development procedure, certain design variables, such as length and diameter, are apt to be fixed as well as combustor operating conditions. Under these conditions, the constraints on certain performance parameters must be relaxed, and an improvement in one performance factor generally is accompanied by a degradation of some other aspect of combustor performance.

7.1.3 NOx Emission Control

The theoretical analysis of NOx emission conducted in this program has indicated the dependence of NOx emission rate on engine pressure ratio, combustion zone residence time, and fuel distribution. (The term "fuel distribution" is used to include both the mean fuel-air ratio and the fuel-air ratio distribution in the primary combustion zone.) Of these three factors, modification of fuel distribution is the only effective approach to controlling NOx emissions by combustor design procedures. The engine pressure ratio strongly affects NOx emission rate, but is independent of combustor design characteristics. On the other hand, the combustion zone residence

time is determined entirely by combustor design characteristics, but its effect on NOx emission rate is relatively small. Thus, it is through fuel distribution that the designer can most effectively control NOx emissions.

The fuel distribution in the combustion zone can be characterized adequately by design parameters which are, or could be, involved in the combustor design process. These parameters are the fuel-air ratios in the primary and intermediate zones, and the primary zone mixedness parameter, S_o . These quantities, therefore, are the design parameters which must be specified properly in order to control NOx emissions. Since these parameters also affect other combustor performance requirements, they provide a basis for relating NOx emission rate to other combustor performance characteristics. This mutual dependence upon combustion zone fuel-air ratio and mixedness underlies the development of NOx emission control criteria.

7.2 CONVENTIONAL COMBUSTORS

7.2.1 Performance Characteristics

It is possible to depict the combustion performance characteristics of a gas turbine combustor in a semi-quantitative manner by employing certain design parameters defined in the previous section. The parameters affecting combustion performance most strongly are the combustion loading parameter (Θ) and the primary zone fuel-air, or equivalence, ratio ($\bar{\Phi}_p$). Using these parameters, combustion efficiency can be plotted as shown in Figure 22. The figure constitutes a performance map for a particular type of combustor and indicates combustion efficiency corresponding to each $\Theta: \bar{\Phi}_p$ operating point. This type of performance map cannot be constructed precisely for a given combustor design without the benefit of experimental data. However, the map is characteristic of well-designed combustors and is useful for discussion of design criteria.

It can be seen from Figure 22 that high combustion efficiency is associated with high values of Θ and values of $\bar{\Phi}_p$ near unity.

With decreasing Θ and changes in $\bar{\Phi}_p$ from this optimum value, combustion efficiency is observed to decrease. The decrease is gradual at first, but becomes precipitous as the efficiency falls toward low values and the blow-out limit. The blow-out limit of the combustor, as a rather gross approximation, may also be considered to represent the combustor ignition limit.

Superimposed on each operating point, the primary zone mixedness parameter, S_o , is shown as a vertical line. The height of this line indicates the spread of equivalence ratios over which combustion actually occurs. It can be seen that if this spread is great, portions of the fuel are burning in regions where combustion efficiency is low or where smoke is formed, even though the mean equivalence ratio is near its optimum condition.

The operating line of a conventional (fixed geometry) combustor is shown in the figure.* The locations of the combustor operating conditions are highly constrained by the requirement that the combustor operate over a range of primary zone equivalence ratios of approximately 2.5:1. This range is typical of the over-all fuel-air ratio of aircraft turbine engine combustors, and with fixed geometry, the primary zone equivalence ratio varies over a similar range. The 100 per cent power condition must be located near the $\bar{\Phi}_p = 1$ condition since excessive smoke is produced at higher values. The value of $\bar{\Phi}_p$ at 100 per cent power cannot be reduced substantially because the low power condition would move out of the stable combustion region. Some relief from this constraint is obtained by increasing Θ through increases in combustor volume. However, the dependence on Θ is small in the normal operating regions so that any gain in performance is small.

7.2.2 Designing for NOx Control

Using the results of the theoretical analysis of NOx emissions, it is possible to construct combustor performance maps depicting NOx emission rate. A different map must be constructed, however, for the new-combustor and modified-combustor design procedures.

* The variable-geometry operating line, also shown, is discussed in Section 7.3.2.

In the following discussion, an illustrative example will be given of an approach to NO emission control using the modified combustor design procedure. Combustor B of the experimental test program will be used as an example with the assumption that the over-all dimensions of the combustor cannot be changed. Approaches to NOx emission reduction will be indicated along with the corresponding reductions in other performance factors.

It has been shown earlier that NOx emissions can be controlled most effectively by variation of the fuel distribution parameters $\bar{\Phi}_p$ and S_o . Thus, an NOx emission map for design purposes might be constructed using these parameters. However, since S_o cannot be evaluated during the design process, a different basis is required. For this purpose, it has been assumed here that the primary zone mixedness factor S_o is related to the pressure loss factor as follows:

$$S_o \sim \left(\frac{\Delta P}{q_{ref}} \right)^{-1}$$

The basis for this assumption is the recognition that the pressure loss factor represents the ratio of air jet energy to the energy of the main flow in the combustor. Thus, this factor is proportional to the energy available for "stirring" the primary zone, and an increase in stirring produces an increase in mixedness, or a decrease in S_o . The assumed relationship between S_o and $\Delta P/q_{ref}$ is a major approximation, but no better basis exists at present for evaluating S_o . Support for this approximation, based upon turbulence theory, is found in Reference 17 in which an approach to the question of imperfect mixing similar to the one adopted here has been used. It has been shown that the decay in the factor S_o does, in fact, change in proportion to the energy input via air jets located at the wall. Since this discussion is intended only to be illustrative, this approximation will be useful. However, for actual combustor design applications, a more accurate relationship between S_o and combustor design variables will be required.

Exhaust NOx concentrations are shown in Figure 23 for Combustor B operating at the take-off condition with wide variations of

$\bar{\Phi}_p$ and S_o . Using the approximate $S_o: \Delta P/q_{ref}$ relationship, these results have been plotted against $\bar{\Phi}_p$ and $\Delta P/q_{ref}$ in Figure 24. This figure can be regarded as an NOx emission performance map for this combustor since it relates NOx emissions to well-defined combustor design parameters. The map is applicable only to the modified-combustor design procedure since it has been constructed with the assumption that over-all combustor geometry is fixed.

The design operating point for the combustor is indicated in the figure. Also indicated is the direction in which the design point might be moved in order to reduce NOx emissions. Since the design parameters $\bar{\Phi}_p$ and $\Delta P/q_{ref}$ are completely controlled by the designer, he is free to move the design point about the map as he chooses. He must, however, be aware of the consequences of his modifications.

It is possible to relate three important combustor performance parameters-- pressure loss fraction, combustion efficiency, and ignitability-- to the same design parameters-- $\bar{\Phi}_p$ and $\Delta P/q_{ref}$ -- which have been used here to map NOx emissions. These relationships will vary with combustor type and design practice, and extensive amounts of performance data would be required to define them precisely. However, for purposes of this discussion, these relationships can be defined in a semi-quantitative manner from available combustor performance data.

The pressure loss fraction is defined (Section 7.1.2) as a function of $\Delta P/q_{ref}$ and combustor size. Since size is assumed fixed in this example, the variation of pressure loss fraction is readily observed to be proportional to variations in $\Delta P/q_{ref}$.

Variations in combustion efficiency can be taken from Figure 22. With combustor size and operating conditions fixed, the loading parameter Θ remains fixed, and combustion efficiency will vary with $\bar{\Phi}_p$ only.

To evaluate variations in ignition performance, an ignition criterion developed by Lefebvre (Ref 18) can be used which states that constant ignition performance corresponds to a constant value of the following parameter:

$$I = f \left[\frac{E_i^{0.25} P^{0.5} T^{2.5}}{U_{ref} (\Delta P/q_{ref})^{0.5}} \right]$$

where E_i = ignition energy and U_{ref} is used to represent the air velocity in the combustion zone. When considering variations in $\bar{\Phi}_p$, we can substitute the inverse of this parameter for U_{ref} since $\bar{\Phi}_p$ is changed by varying the airflow rate in the combustion zone. Then, assuming E_i is constant, the ignition parameter can be redefined as

$$\frac{I}{f(E_i)} = f_1 \left[\frac{P^{0.5} T^{2.5} \bar{\Phi}_p}{(\Delta P/q_{ref})^{0.5}} \right]$$

The most difficult ignition requirement for an aircraft engine is reignition at high altitude, and the combustor inlet pressure and temperature at ignition are uniquely related to altitude. Thus, it is possible by the above relationship to determine the variation in altitude reignition capability. Assuming that the engine can be reignited at 35,000 ft altitude at present, reductions in this maximum ignition altitude can be calculated for changes in $\bar{\Phi}_p$ and $\Delta P/q_{ref}$.

The design performance parameter relationships discussed above are presented graphically in Figure 25. This figure is of the same format as the NOx emissions map for Combustor B. The change in operating condition required to reduce NOx emissions is indicated, and the associated reductions in pressure loss fraction, combustion efficiency, and reignition altitude are shown. Also shown is an estimate of the minimum $\bar{\Phi}_p$ for combustor cooling. This estimate is based on the assumptions that 25 per cent of the total airflow is required for film cooling and 30 per cent is required for satisfactory dilution zone performance, and that the latter requirement decreases with increasing $\Delta P/q_{ref}$.

The performance map in Figure 25 indicates that substantial performance losses would be associated with reducing NOx emissions by variations in $\bar{\Phi}_p$ and $\Delta P/q_{ref}$. The relationships shown in the figure

are approximate, but they are considered to be representative of the performance changes associated with the modified-combustor design procedure. With the new-combustor design procedure, where combustor size is not fixed, the performance changes need not be so severe.

The performance map of Figure 25 indicates only the performance losses at the 100 per cent power condition. Performance losses also would occur at reduced power conditions, particularly at idle power. Because of the fixed relationship between the value of $\bar{\Phi}_p$ at 100 per cent and idle power indicated in Figure 22, any reduction in $\bar{\Phi}_p$ tends to cause a rapid reduction in combustion efficiency at idle. This loss is, of course, accompanied by increased CO and HC emissions. With the modified-combustor design procedure, this loss can be alleviated somewhat by increasing the idle power level, but it is very likely that the idle condition performance will be a limiting factor if NO emissions are to be controlled by reduction of $\bar{\Phi}_p$.

As indicated earlier, this discussion is intended to illustrate a method by which an existing combustor could be redesigned for low NOx emissions. If, instead, a combustor for a new engine were to be designed, variations in combustor geometry and fuel nozzle characteristics could be employed to minimize NOx emissions. It is likely that the primary zone mixedness parameter, S_o , is highly dependent upon fuel nozzle characteristics. Thus, a greater range of design conditions would be available and the combustor performance losses associated with NOx emission control probably would not be as great as for a modified combustor.

7.3 ALTERNATIVE APPROACHES TO NOx EMISSION CONTROL

7.3.1 Use of Water Injection

The dominant factor influencing the nitric oxide emission rate is the peak temperature in the primary zone of the combustor. This temperature may be significantly reduced by the use of water addition into the combustion zone, and the water may be added either at the compressor exit or directly into the primary zone. The latter

approach is more efficient in terms of the mass flow rate of water required as approximately only one quarter of the airflow passes through the primary zone.

With direct water addition to the primary zone, there is a greater possibility of a degradation of combustion performance than with upstream injection. However, recent experience with direct water injection (Ref 19) indicates that other combustion performance parameters can be maintained while NOx emissions are reduced. The temperature changes brought about by water injection reduce the nitric oxide levels very significantly. Estimates have been made of this reduction for the combustors tested in this program and the results are shown in Figures 26 and 27. The figures apply to the case of water injection into the compressor exit and are based upon the experimental NOx emission data obtained by the methods described earlier. The estimates have been made based upon the following assumptions:

- a. That all the water injected vaporizes and mixes completely with the compressor air before entry into the combustor. An enthalpy balance then determines the reduction in combustor inlet temperature that results from this action.
- b. That the change in nitric oxide emission level that results from a reduction in temperature rise in the combustor (due to the water), is related to the mass average flame temperature at the primary zone exit. An enthalpy balance accounting for the presence of the water vapor can determine the temperature reduction and the corresponding (higher) value of air-fuel ratio which has the same flame temperature. Thus, if the nitric oxide versus air-fuel ratio is known for the inlet temperature defined by assumption a, the nitric oxide emission level may be estimated for a prescribed mass flow of water.

Clearly, these calculations only produce estimates of the effect of water injection but these estimates will be sufficiently accurate to determine the effectiveness of the method. The results are encouraging for both combustors tested (see Figs 26 and 27), particularly at the lower air-fuel ratios (less than 70) where a water-to-fuel ratio of 1.0 generally reduces nitric oxide emissions by 50 per cent. The effect of water injection is shown to diminish, however, as the air-fuel ratio increases.

7.3.2. Variable Geometry Combustor Design

Another potentially effective approach to NO emission control is based on the use of combustors with variable geometry. The purpose of the variability is to maintain independent control of the primary zone fuel-air ratio as the over-all combustor fuel-air ratio changes with power level. This control of $\bar{\Phi}_p$ is accomplished by controlling the fraction of the total airflow entering the primary zone. With independent control of $\bar{\Phi}_p$, the combustor can be operated so that NOx emission rates are low over the entire power range. The most effective operating conditions for NOx control would be at lean fuel-air ratios ($\bar{\Phi}_p < 1.0$). A combustor operating line corresponding to this condition is shown in Figure 22. For this approach to be effective, a well-mixed primary zone (low S_o) is required so that very little fuel is burned near stoichiometric fuel-air ratios. An additional requirement is an increase in combustor size to maintain high combustion efficiency at the lower combustion temperatures. Because of this requirement, the approach is not applicable to existing engines where combustor size is fixed. But variable geometry could be used in future engines as a means for controlling NOx emissions with little or no loss in other performance characteristics. From the predicted effects of fuel distribution on NOx emission rate, it is estimated that reductions of 50 to 80 per cent can be achieved in NO emission rate at high power conditions. The approach also would improve combustion efficiency and CO and HC emissions at low power, and would improve ignition performance. Thus, variable geometry is an attractive control method, particularly from the standpoint of emission control effectiveness.

7.3.3. Staged Combustion

Another potential approach to NOx emission control is based on the concept of staged combustion or staged fuel injection. This combustor design concept may take any of several forms, but a typical approach would involve the following features:

- a. A small primary combustion zone operating at a lean fuel-air ratio ($\bar{\Phi}_p \approx 0.8$) with well-mixed fuel injection. The primary zone would provide all power required for idle operation, and would act as a pilot for other combustion zones downstream.
- b. One or more secondary combustion zones into which fuel is injected directly, again in a well-mixed fashion. Fuel and air would be distributed so that fuel-air ratios would be lean throughout the combustion zone.

This approach is attractive in that it would not require variable geometry. It probably would require a relatively long combustor and a complex fuel control system. Control of NO_x emissions would result from the low combustion temperatures associated with lean fuel-air ratios. The control effectiveness would increase with the number of combustion zones utilized. However, the fuel system complexity also would increase.

The concept of staged combustion has not been thoroughly evaluated as an NO_x emission control technique. Considerable effort will be required to determine the merits of this approach.

7.4 CONCLUSIONS

The following conclusions have been formulated concerning criteria for NO_x emission control:

- a. NO_x emission rates relate to fundamental combustor design parameters which also influence other major combustion performance factors. This interrelationship between NO_x emissions and other combustion performance factors establishes a sound basis for quantitative NO_x emission control criteria.
- b. NO_x emission rates from conventional combustors can be reduced by modification of fuel distribution parameters. However, NO_x reduction may be accompanied by significant reductions in other performance factors such as combustion efficiency and reignition altitude. These performance losses will probably be more severe in a modified-combustor design procedure where combustor size is fixed than in a new-combustor design procedure.

- c. Water injection is effective in reducing NOx emission from conventional combustors. Emission rate reductions of 50 per cent at high power levels can be obtained with water injection rates comparable to fuel flow rates. Increased control may be obtained with increased water injection rates, or by localizing injection of water into the combustion zone.
- d. Reductions in NOx comparable to those achievable by the use of water injection can be obtained through the development of advanced combustor design concepts such as variable geometry and staged combustion. These concepts are, however, more applicable to new engine designs rather than existing designs.

8. REFERENCES

1. Nature and Control of Aircraft Engine Exhaust Emissions (NREC Report No. 1134-1), Northern Research and Engineering Corporation, Cambridge, Mass., November, 1968.
2. Platt, M., et al, The Potential Impact of Aircraft Emissions Upon Air Quality (NREC Report No. 1167-1), Northern Research and Engineering Corporation, Cambridge, Mass., 1971.
3. Bastress, E. K., et al, Assessment of Aircraft Emission Control Technology (NREC Report No. 1168-1), Northern Research and Engineering Corporation, Cambridge, Mass., 1971.
4. The Design and Performance Analysis of Gas-Turbine Combustion Chambers, Volume I: Theory and Practice of Design and Volume II: Design Methods and Development Techniques (NREC Report Nos. 1082-1 and 1082-2), Northern Research and Engineering Corporation, Cambridge, Mass., 1964.
5. Caretto, L. J., Sawyer, R. F., and Starkman, E. B., The Formation of Nitric Oxide in Combustion Process, Presented at 1968 Technical Meeting, Central States Section, The Combustion Institute, March 26-27, 1968.
6. Bartok, W., et al, Systems Study of Nitrogen Oxide Control Methods for Stationary Sources (Esso Report No. GR-1-NOS-69), Interim Status Report to National Air Pollution Control Administration, Esso Research and Engineering Company, May, 1969.
7. Newhall, H. K., Kinetics of Engine-Generated Nitrogen Oxides and Carbon Monoxide, Presented at the Twelfth Symposium (International) on Combustion, The Combustion Institute, 1968.
8. Lavoie, G. A., Heywood, J. B., and Keck, J. C., Experimental and Theoretical Study of Nitric Oxide Formation in Internal Combustion Engines (Publication No. 69-10), Fluid Mechanics Laboratory, Massachusetts Institute of Technology, Cambridge, Mass., November, 1969, published in Combustion Science and Technology, vol. 1, 1970, pp. 316-326.
9. Fletcher, R. S. and Heywood, J. B., A Model for Nitric Oxide Emissions from Aircraft Gas Turbine Engines (AIAA Paper No. 71-123), American Institute of Aeronautics and Astronautics, AIAA 9th Aerospace Sciences Meeting, New York N. Y., January 25-27, 1971.
10. Lavoie, G. A., Nitric Oxide Measurements in an Internal Combustion Engine by Visible and Near Infra-Red Emission Spectroscopy, ScD Thesis, Massachusetts Institute of Technology, Cambridge, Mass., February, 1970.
11. Baulch, D. L., Drysdale, D. D., Horne, D. G., and Lloyd, A. C., "Critical Evaluation of Rate Data for Homogeneous Gas Phase Reactions of Interest in High-Temperature Systems" (Report No. 4), Department of Physical Chemistry, Leeds University, United Kingdom, December, 1969.

8. REFERENCES (CONTINUED)

12. Hodge, J., Cycles and Performance Estimation, Butterworth Scientific Publications, London, England, 1955.
13. Bogdan, L. and McAdams, H. T., Analysis of Aircraft Exhaust Emission Measurements (CAL No. NA-5007-K-1), Cornell Aeronautical Laboratory, Inc., Cornell University, Buffalo, N. Y., October 15, 1971.
14. Halstead, C. J. and Munro, A. J. E., The Sampling, Analysis and Study of the Nitrogen Oxides Formed in Natural Gas/Air Flames, Shell Research Ltd., Egham Research Laboratories, Egham, Surrey, United Kingdom (to be published).
15. Jackson, S. R. and Odgers, J., "Factors Influencing Heat Release in Combustion Chambers and Consideration of the Related Materials and Structures", Combustion in Advanced Gas Turbine Systems, Proceedings of an International Propulsion Symposium held at the College of Aeronautics, Cranfield, England, April, 1967.
16. Greenhough, V. W., and Lefebvre, A. H., Some Applications of Combustion Theory to Gas Turbine Development, Sixth Symposium (International) on Combustion, Reinhold Publishing Corporation, New York, Chapman and Hall, Ltd., London, August 19-24, 1956.
17. Evangelista, J. J., Shinnar, R., and Katz, S., The Effect of Imperfect Mixing on Stirred Combustion Reactors, Twelfth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Penna., 1969.
18. Lefebvre, A. H., "Ignition Theory and its Application to the Altitude Relighting Performance of Gas Turbine Combustors", Combustion & Heat Transfer in Gas Turbine Systems, Cranfield International Propulsion Symposium, The College of Aeronautics, Cranfield, Bedford, England, 1969.
19. Klapatch, R. D. and Koblish, T. R., Nitrogen Oxide Control with Water Injection in Gas Turbines, (ASME Paper No. 71-WA/GT-9), American Society of Mechanical Engineers, Presented at ASME 92nd Winter Annual Meeting, Washington, D. C., December 1, 1971.

9. TABLES

TABLE 1

COMBUSTOR CONDITIONS INVESTIGATED IN
THE MODEL SENSITIVITY ANALYSIS

A. Combustor Geometry and Operating Conditions

Volume of Primary Zone (V_p)	88.5 in ³
Length of Intermediate Zone (X_L)	7.0 in
Length of Intermediate and Dilution Zone (X_{END})	12.5 in
Primary Zone Mean Effective Equivalence Ratio ($\bar{\Phi}_E$)	0.8
Combustor Inlet Pressure (P_{in})	6.5 atm
Combustor Inlet Temperature (T_{in})	700 deg K
Total Airflow to the Combustor ($M_{A_{TOT}}$)	7.56 lb/sec

B. Model Parameters

Values Tested				
		Nominal**		
S_o	0.1	0.2	0.3	0.4
β^*	0.6	0.8	1.0	--
$(dM_a/dX)_o$	--	0.2	0.4	0.7
C_N^*	2	5	10	20
A_1^*	0.2	0.5	1.0	--
A_2^*	0.2	0.5	1.0	--
A_3^*	0.5	1.0	1.5	--

Note: Only one variable was changed at a time.

* For definition of variables, see Section 3.3.

** Nominal values for A_1 , A_2 , and A_3 are the anticipated values based upon the considerations given in Reference 4. Nominal values for S_o , C_N are estimated. Nominal value for β determined from Figure 9, and nominal value for $(dM_3/dX)_o$ determined as described in Volume 3, Appendix XVI.

TABLE 2.
KINETIC DATA FOR THE NITRIC OXIDE REACTION SCHEME

	Reaction No.	A_i (cm ³ /sec gm-mole (deg K) ^{n_i})	n_i	E_i (kcal/gm-mole)
ICODE = 1 (from Ref 10)	1	1.2046×10^{13}	0.0	0.0
	2	1.2046×10^{13}	0.0	7.1
	3	4.2161×10^{13}	0.0	0.0
	4	3.0115×10^{13}	0.0	10.8
	5	3.6138×10^{13}	0.0	24.0
	6	4.8184×10^{13}	0.0	24.0
ICODE = 2 (from Ref 11)	1	3.1×10^{13}	0.0	0.334
	2	6.4×10^9	1.0	6.25
	3	4.1×10^{13}	0.0	0.0
	4	2.9513×10^{13}	0.0	10.77
	5	3.8146×10^{13}	0.0	24.1
	6	4.5775×10^{13}	0.0	24.1
ICODE = 3 (from Ref 9)	1	3.0717×10^{13}	0.0	0.33
	2	1.3251×10^{10}	1.0	7.1
	3	4.2161×10^{13}	0.0	0.0
	4	2.9513×10^{13}	0.0	10.77
	5	3.8146×10^{13}	0.0	24.1
	6	4.5775×10^{13}	0.0	24.1
ICODE = 4 (from Ref 9)	1	1.0239×10^{13}	0.0	0.0
	2	3.7945×10^{12}	0.0	7.0
	3	4.1559×10^{13}	0.0	0.0
	4	2.9513×10^{13}	0.0	10.77
	5	3.8146×10^{13}	0.0	24.1
	6	4.5775×10^{13}	0.0	24.1

where

$$k = A_i T^{n_i} \exp(-E_i/RT)$$

T = Temperature in deg K

$$R = 1.987 \times 10^{-3} \text{ kcal/gm-mole deg K}$$

TABLE 3
CHANGES IN NITRIC OXIDE EMISSION LEVELS PREDICTED
USING FOUR ALTERNATIVE SETS OF KINETIC DATA

Kinetic Data ICODE*	Reactions** 1-6	Reactions** 1-3
1	1.00	0.98
2	2.22	2.21
3	2.05	2.04
4	0.86	0.85

* See Table 2.

** Values are quoted relative to ICODE = 1 results, that is the reaction data used in Reference 10.

TABLE 4a - SUMMARY OF TEST DATA
COMBUSTOR A

	Combustor Conditions						Emission Levels			
	P psia	T deg K	T deg R	M _a lb/sec	AFR	M _a T/P	NO ppmV	CO ppmV	HC ppmV	(M) **
a	85	576	1037	5.00	72	34	46	480	--	1
	81	707	1273	3.60	52	31	184	--	--	1
	87	703	1265	4.15	57	34	137	245	--	1
	90	712	1282	3.67	58	29	160	206	0.8	1
	79	728	1310	3.61	64	33	134	250	--	1
	91	705	1269	4.13	70	32	102	275	--	1
	82	687	1237	3.43	71	29	101	340	--	1
	84	700	1260	3.51	76	29	80	--	--	1
	88	698	1256	4.00	79	32	58	--	--	1
	89	713	1283	4.23	83	34	34	--	--	1
	75	683	1229	3.85	143	35	21	245	--	1
	89	8.6	1469	3.19	63	29	192	170	--	1
	83	688	1238	2.74	59	23	136	125	--	1
	85	711	1280	5.03	61	42	110	190	0.6	--
b	119	579	1042	6.22	56	30	111	255	--	1
	118	598	1076	6.31	67	32	83	--	--	1
	118	581	1046	5.61	71	28	58	290	1.3	1
	123	578	1040	5.89	75	28	56	233	1.3	1
	116	590	1062	6.63	82	34	56	380	--	1
	114	595	1071	5.67	95	30	32	300	3.1	1
	112	603	1085	6.16	153	33	19	300	3.1	1
	123	675	1215	5.72	54	31	264	205	--	1
	119	688	1238	5.57	59	32	228	195	--	1
	113	677	1218	5.02	64	30	122	182	--	1
	130	692	1245	5.64	67	30	122	255	2.0	1
	131	698	1256	5.75	72	31	104	265	2.0	1
	110	691	1243	4.97	74	31	88	210	--	1
	108	695	1251	5.27	104	24	53	--	0.9	1
	102	695	1251	5.06	116	34	44	137	0.9	1

Fuel: Aviation Kerosene

* Calibrated as hexane

** Method of NO measurement: 1 = NDIR
2 = Chemiluminescent

TABLE 4b - SUMMARY OF TEST DATA
COMBUSTOR A

Combustor Conditions						Emission Levels			
P	T		M _a	AFR	M _a T/P	NO	CO	HC	(M)
psia	deg K	deg R	lb/sec			ppmV	ppmV	ppmV	**
123	820	1476	4.09	53	27	376	120	1.2	1
123	852	1533	4.04	53	28	340	--	1.3	1
124	845	1521	4.25	66	29	269	167	1.2	1
119	874	1573	4.15	66	30	254	174	1.3	1
115	855	1539	4.11	68	30	213	--	1.3	1
117	852	1533	4.25	89	31	155	133	0.8	1
c 36	402	724	0.93	78	10	33	760	Sat.	1
42	401	722	0.91	44	9	73	1420	Sat.	1

Fuel: Aviation Kerosene

* Calibrated as hexane

** Method of NO measurement: 1 = NDIR
2 = Chemiluminescent

TABLE 5a - SUMMARY OF TEST DATA
COMBUSTOR b

Combustor Conditions						Emission Levels				
	P	T		M _a	AFR	M _a T/P	NO	CO	HC	(M)
	psia	deg K	Deg R	lb/sec			ppmV	ppmV	ppmV	**
a	89.7	583	1049	6.10	70	40	81	120	1.0	1
	89.7	583	1049	6.10	75	40	72	--	--	2
	87.2	576	1036	6.10	86	40	69	67	1.0	1
	87.2	576	1036	6.10	87	40	65	--	--	2
	86.7	588	1058	6.16	92	42	69	113	2.0	1
	86.7	588	1058	6.16	92	42	63	--	--	2
	87.6	593	1067	5.80	113	39	57	93	--	1
	88	588	1058	5.97	126	40	34	134	--	1,2
	91	683	1229	5.16	56	39	153	87	--	1
	91	683	1229	5.16	56	39	148	--	--	2
	86	687	1236	4.99	62	40	152	100	--	1
	86	687	1236	4.99	62	40	149	--	--	2
	83	703	1265	5.04	75	43	148	87	--	1
	83	703	1265	5.04	75	43	144	--	--	2
	82	703	1265	5.09	96	44	115	80	--	1
	82	703	1265	5.09	96	44	113	--	--	2
	80	708	1274	5.31	129	47	76	90	--	1
	80	708	1274	5.31	129	47	76	--	--	2
	82	797	1434	4.61	66	45	235	100	1.0	1
	82	797	1434	4.61	71	45	215	--	--	2
	85	797	1434	5.03	93	47	169	67	1.5	1
	85	797	1434	5.03	100	47	150	--	--	2
	82	827	1488	4.77	107	48	169	67	3.5	1
	82	827	1488	4.77	115	48	144	--	--	2
	37	393	707	3.66	127	30	14	652	--	1
	37	393	707	3.66	127	39	3	--	--	2
	28	392	705	3.62	76	51	20	500	--	1
	28	392	705	3.62	76	51	16	--	--	2

Fuel: Aviation Kerosene

* Calibrated as hexane

** Method of NO measurement: 1 = NDIR
2 = Chemiluminescent

TABLE 5b - SUMMARY OF TEST DATA
COMBUSTOR B

Internal Probe Measurement, $x = 3$ inches

Combustor Conditions							Emission Levels		
r inches	P psia	T deg K	T deg R	M_a lb/sec	AFR	$M_a T/P$	NO ppmV	CO ppmV	(M) *
Exit	71	595	1071	5.75	85	48	68	98	2
Wall	71	600	1080	5.86	88	50	133	1750	2
3.0	71	593	1067	5.81	88	49	143	2050	2
2.5	72	598	1076	5.91	89	49	150	2400	2
2.0	71	578	1040	5.86	89	48	156	3000+	2
1.5	70	594	1069	5.80	88	49	216	+	2
Exit	69	588	1058	5.83	88	50	56	--	2
Exit	66	600	1080	5.82	88	53	60	150	2
2.0	68	605	1089	5.99	90	53	162	2200	2
1.5	68	583	1049	5.94	89	51	205	+	2
1.0	67	581	1045	5.88	88	51	278	+	2
0.5	68	583	1049	5.93	88	51	305	+	2
0.0	67	581	1045	5.78	86	50	340	+	2
Exit	68	595	1071	5.93	88	52	66	--	2

Approximate values of mass average concentrations of pollutant species calculated to be: NO = 211, CO = 7000+

Fuel: Aviation Kerosene

* Method of NO measurement: 1 = NDIR, 2 = Chemiluminescent

r Distance from center line

+ Assume equilibrium values

TABLE 5c - SUMMARY OF TEST DATA
COMBUSTOR B

Internal Probe Measurements, X = 7 inches

Combustor Conditions							Emission Levels		
\neq r inches	P psia	T deg K	T deg R	M_a lb/sec	AFR	M_a T/P	NO ppmV	CO ppmV	(M) ***
Exit	73	599	1078	5.94	87	49	59	120	2
Wall	71	593	1067	5.86	86	49	33	340	2
3.0	71	595	1071	5.86	87	49	56	400	2
2.5	72	575	1035	5.98	89	48	115	620	2
Exit	70	596	1072	5.85	87	50	54	146	2
2.0	71	581	1045	5.95	89	49	125	486	2
1.5	71	584	1051	5.98	90	49	112	340	2
Exit	72	594	1069	5.98	90	49	54	142	2
1.0	71	592	1065	5.95	90	50	122	333	2
0.5	72	593	1067	6.03	91	50	132	340	2
0.0	70	591	1063	6.03	92	51	--	433	2

Approximate value of mass average concentrations of pollutant species
calculated to be: NO = 120 ppm, CO = 425 ppm

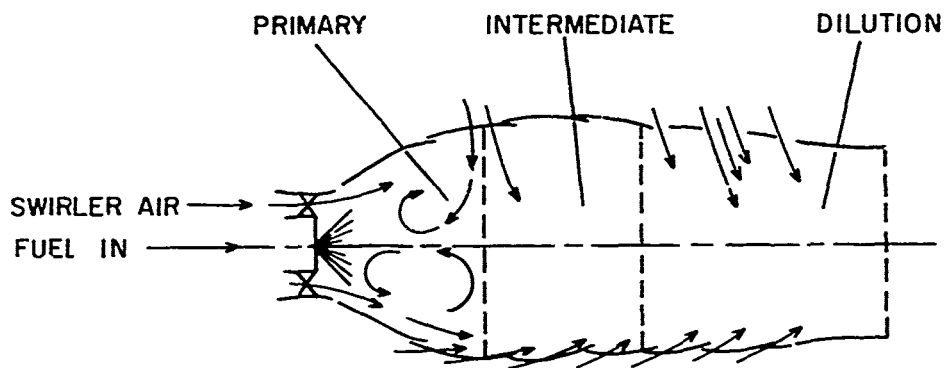
Fuel: Aviation Kerosene

* Calibrated as hexane

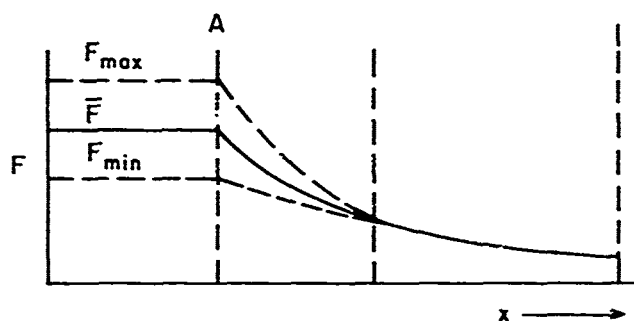
*** Method of NO measurement: 1 = NDIR, 2 = Chemiluminescent

\neq Distance from center line

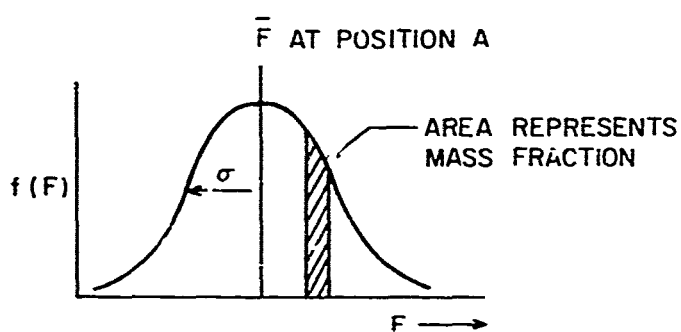
10. FIGURES



(a) CROSS SECTION of COMBUSTOR LINER
SHOWING MEAN FLOW PATTERN



(b) DISTRIBUTION of MIXTURE RATIO F ,
ALONG LINER LENGTH



(c) DISTRIBUTION of MASS AS A FUNCTION
of MIXTURE RATIO and POSITION

Figure 1 - ASSUMED FLOW AND DISTRIBUTION PATTERNS
THROUGHOUT COMBUSTOR LINER

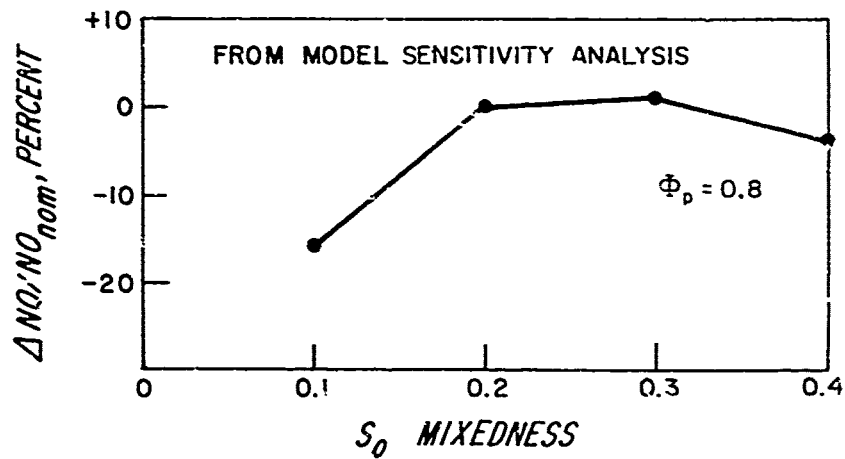
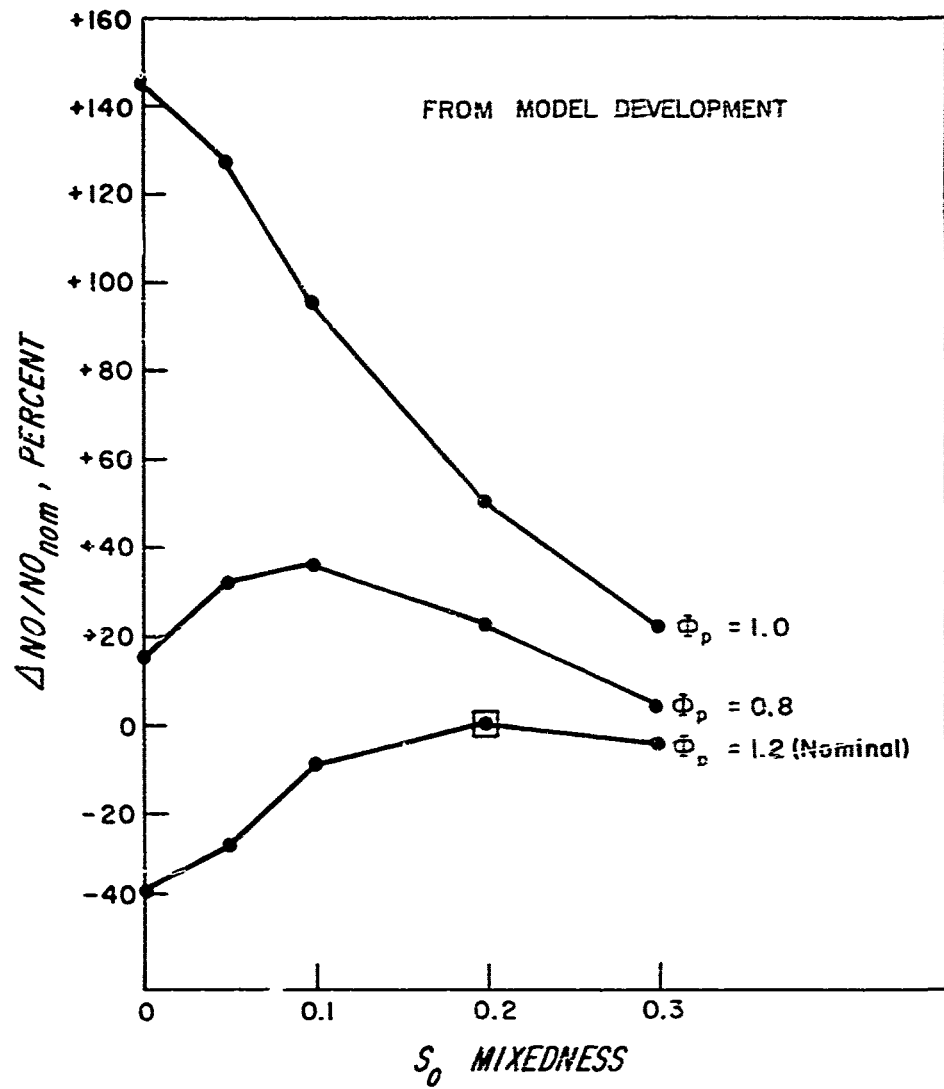
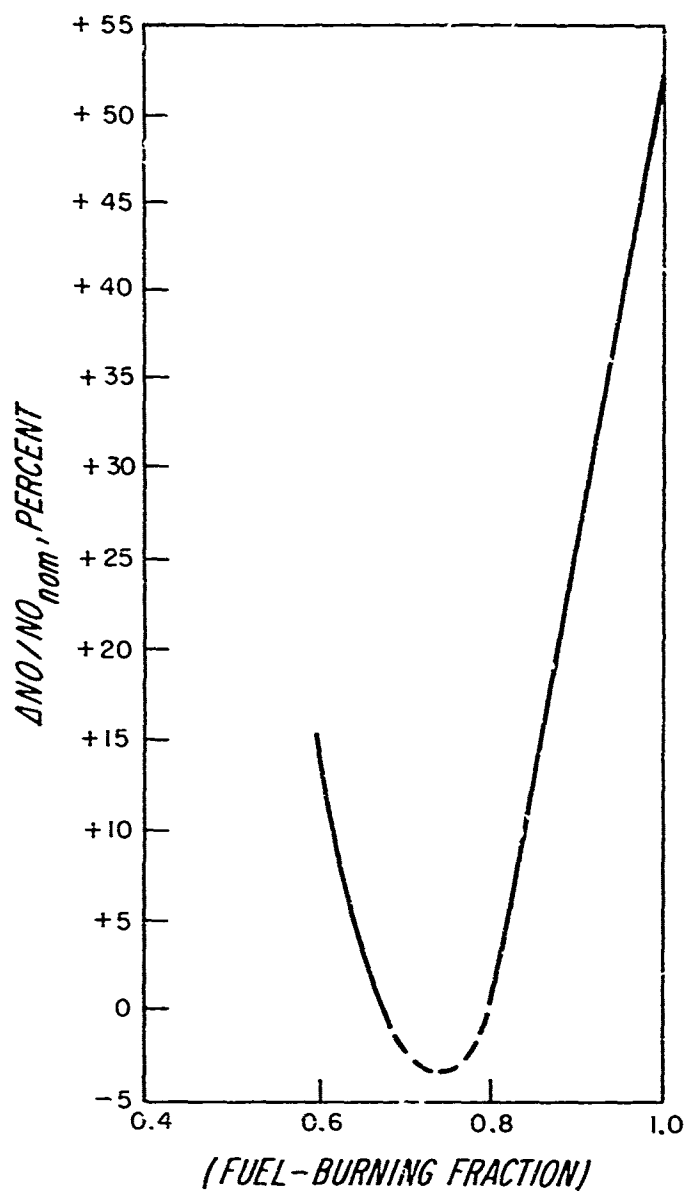
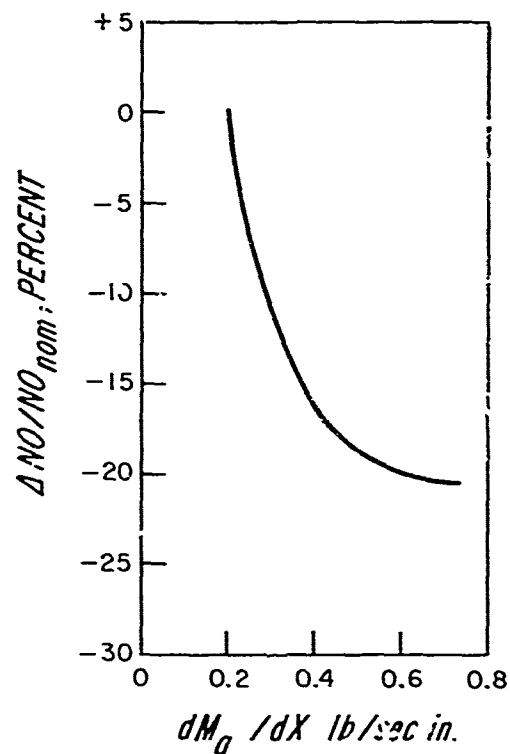


Figure 2 - THE EFFECT OF PRIMARY ZONE MIXEDNESS UPON NITRIC OXIDE EMISSION LEVELS



(a). EFFECT of β



(b). EFFECT of dM_0/dX

Figure 3 - EFFECT OF PRIMARY ZONE FUEL-BURNING FRACTION AND DILUTION AIR MIXING RATE UPON PREDICTED NITRIC OXIDE EMISSIONS

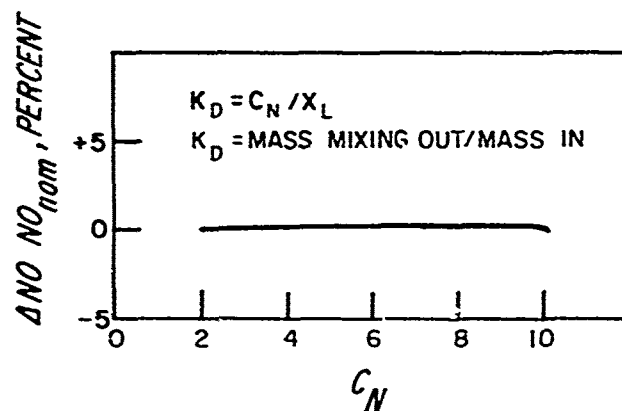
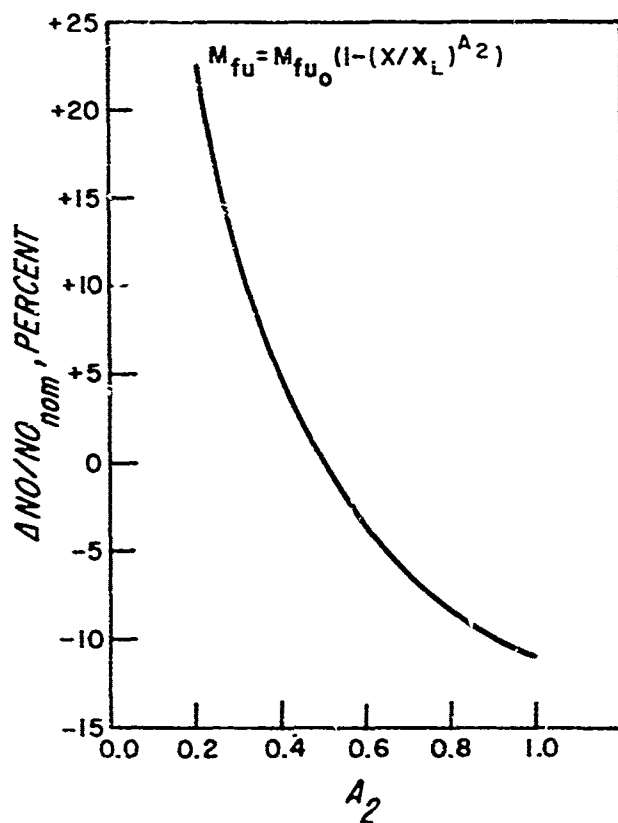
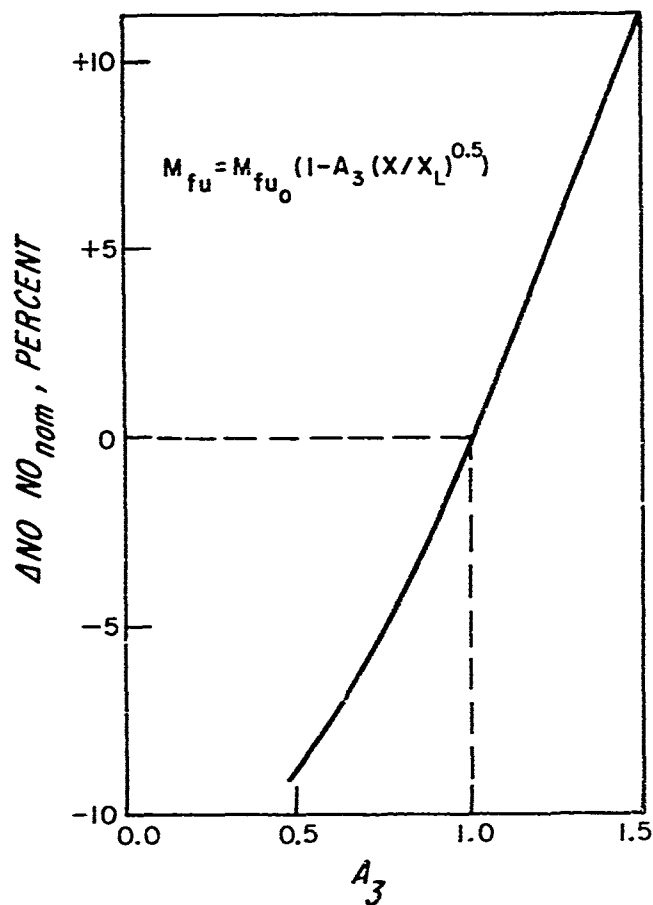
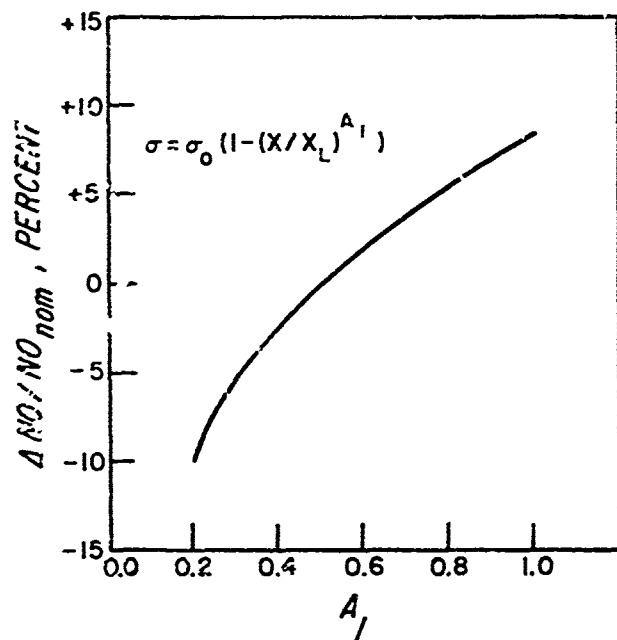


Figure 4 - THE EFFECT OF INTERMEDIATE ZONE MIXING BEHAVIOR UPON NITRIC OXIDE EMISSION LEVELS

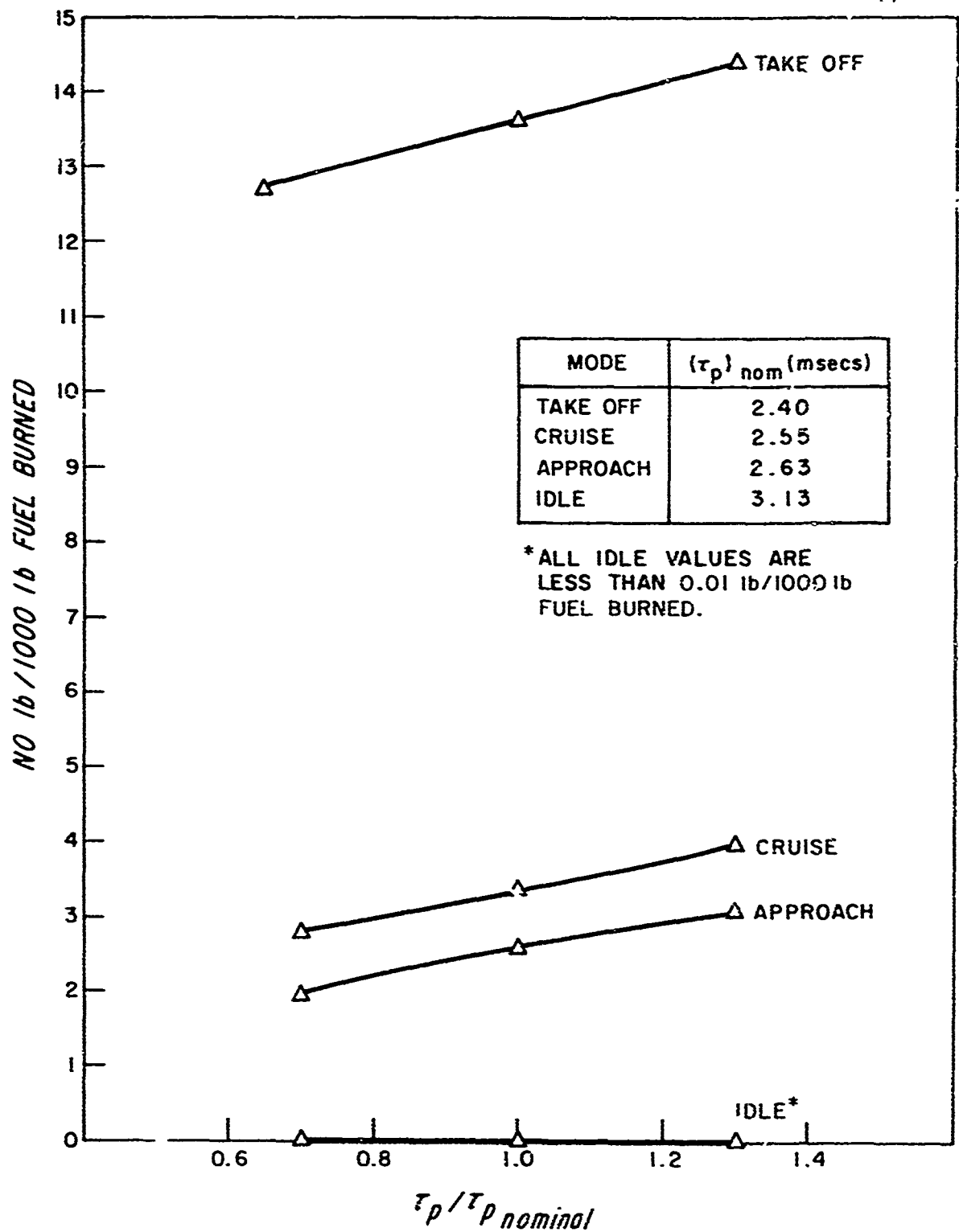


Figure 5- EFFECT OF PRIMARY ZONE
RESIDENCE TIME ON NO_x EMISSION PREDICTIONS

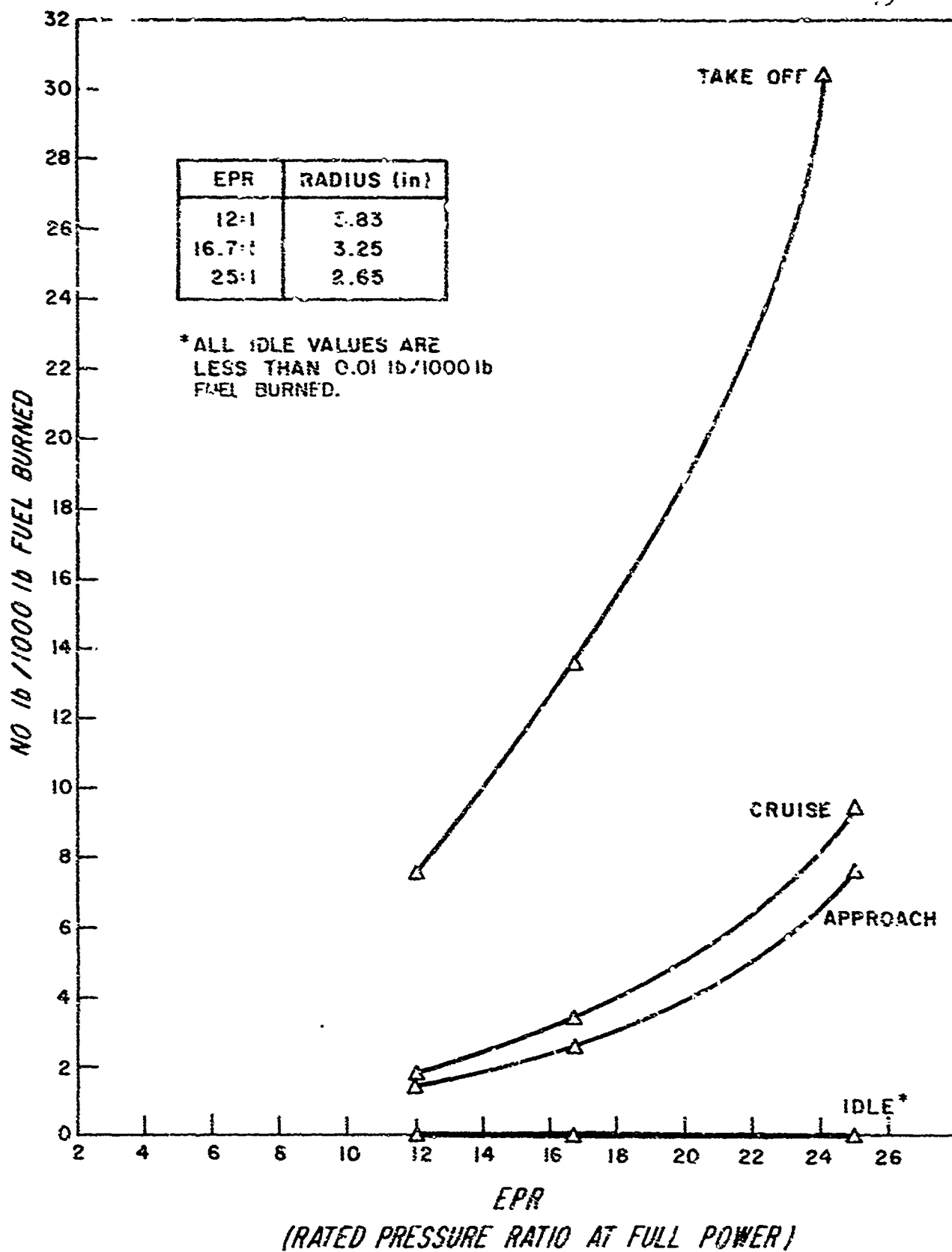
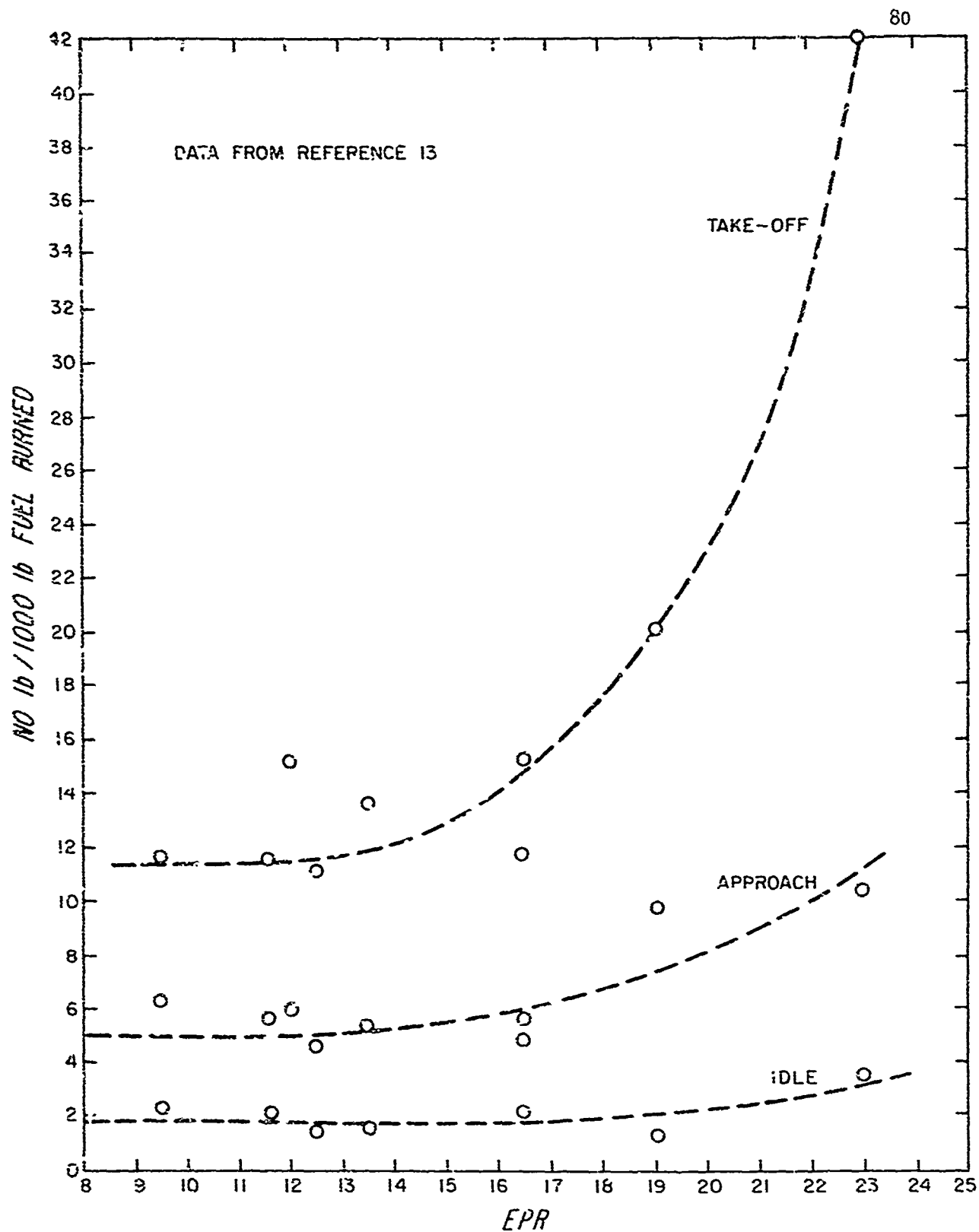
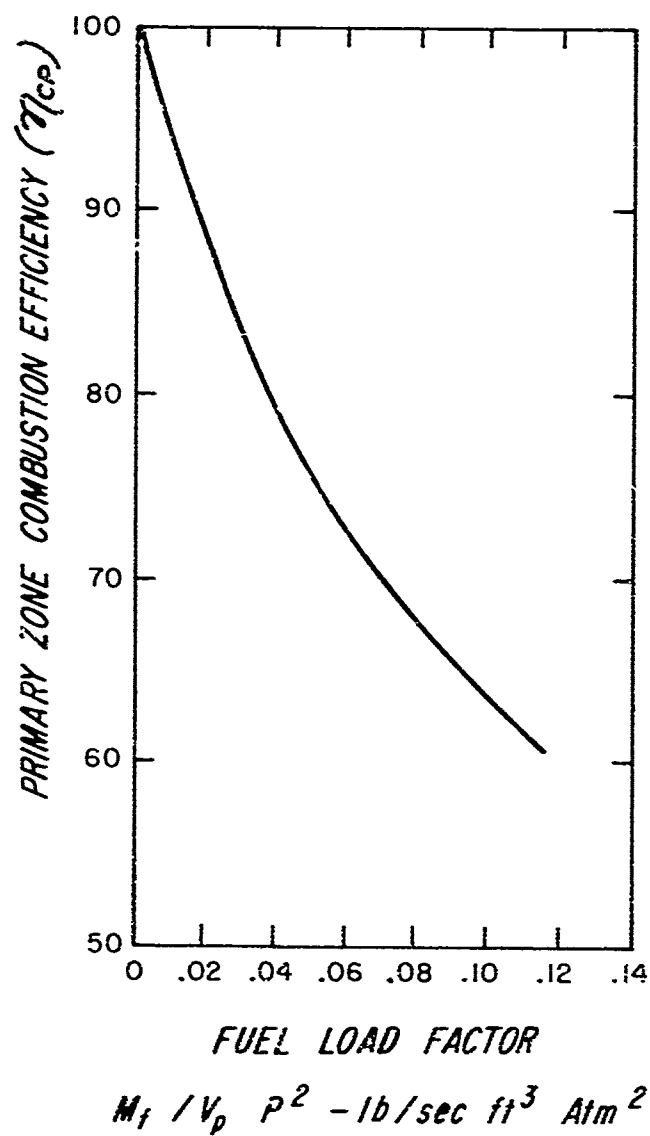


Figure 7 - EFFECT OF ENGINE PRESSURE RATIO UPON NO_x EMISSION PREDICTIONS



(Rated Pressure Ratio at Full Power)

Figure 8 - MEASURED EFFECT OF ENGINE PRESSURE RATIO UPON NO_x EMISSIONS



REPRODUCED FROM REFERENCE 15

Figure 9 - PRIMARY ZONE
COMBUSTION EFFICIENCY CORRELATION

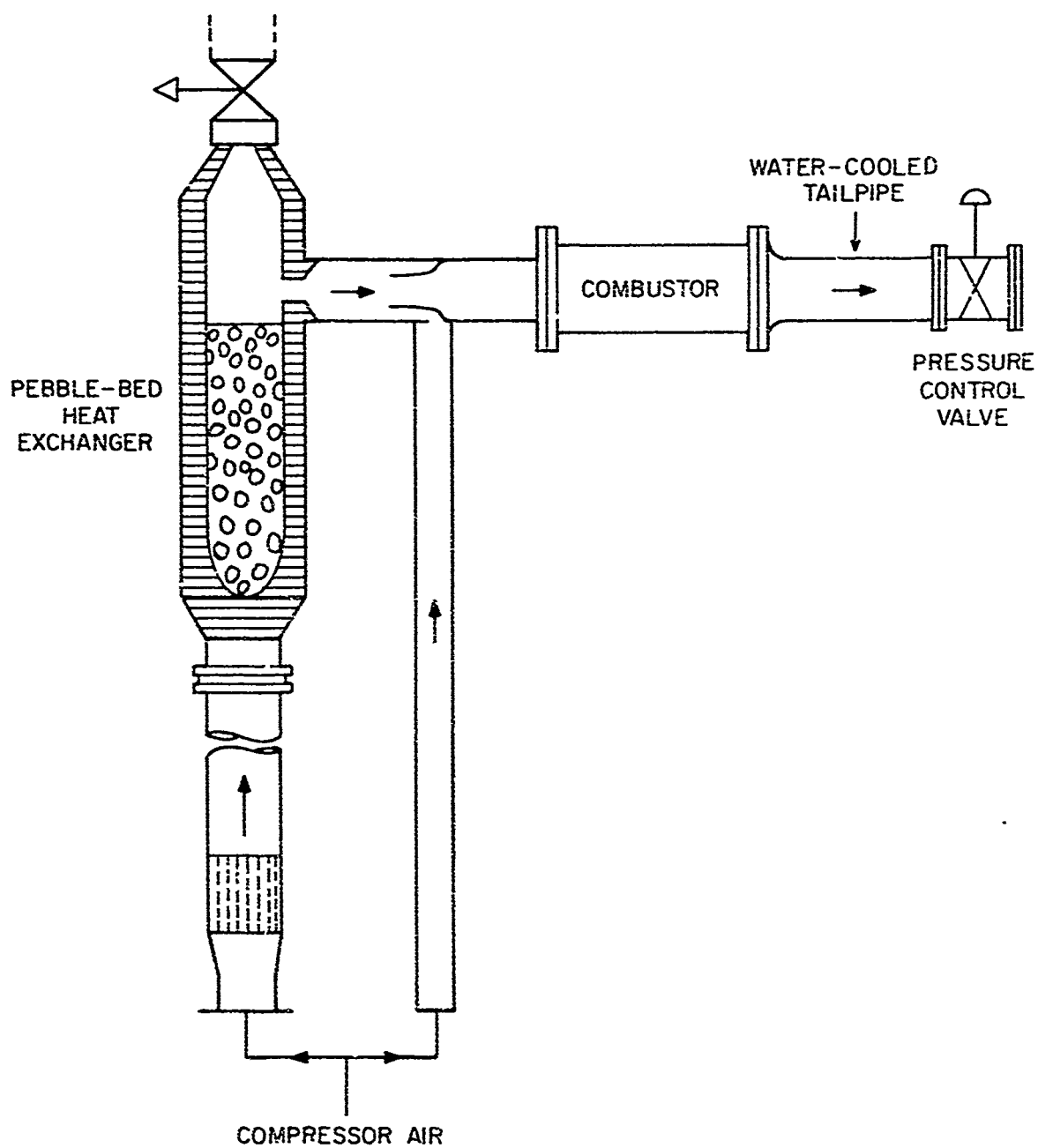


Figure 10 - COMBUSTOR TEST ARRANGEMENT

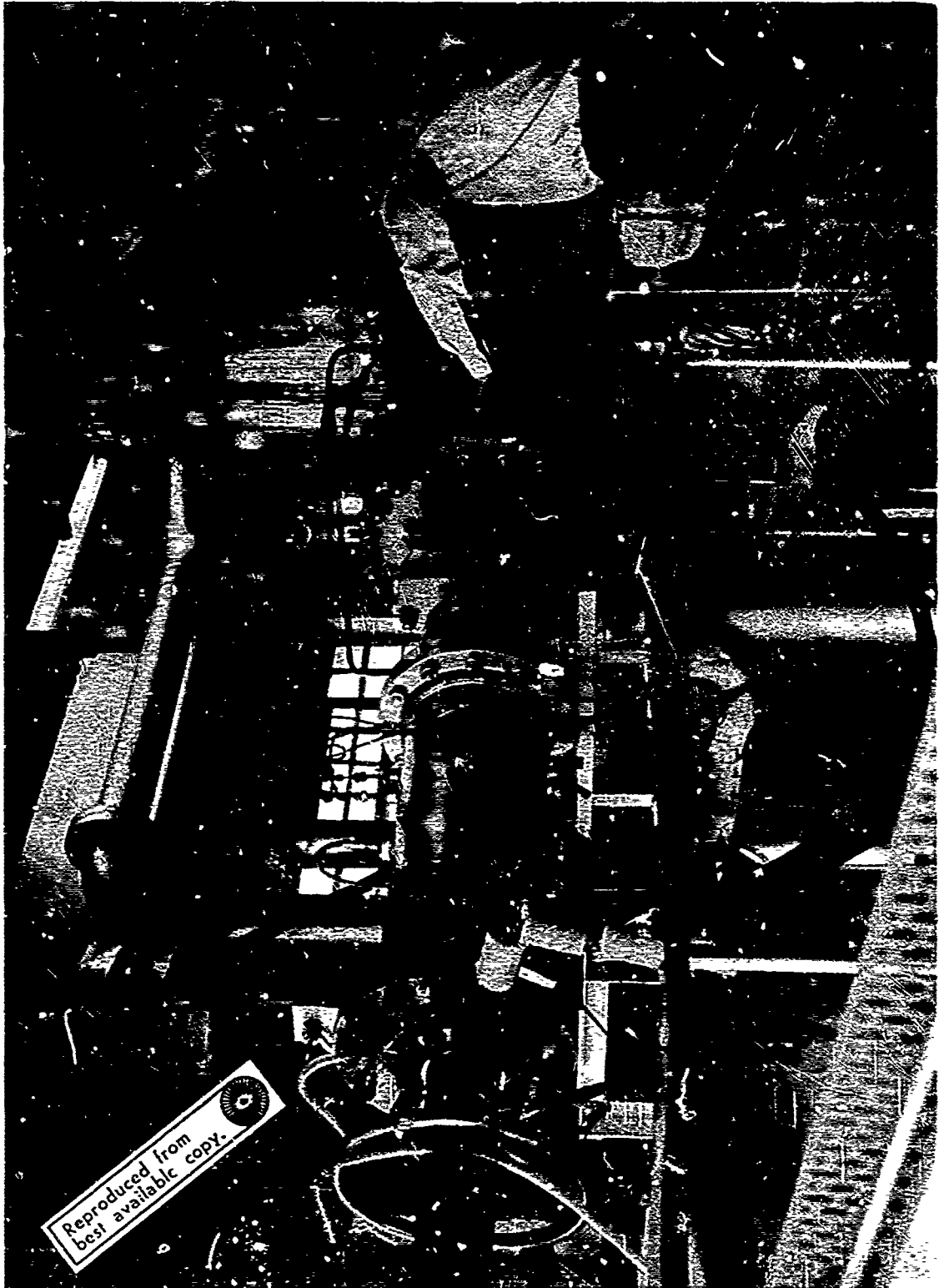


Figure 11 - THE TEST FACILITY

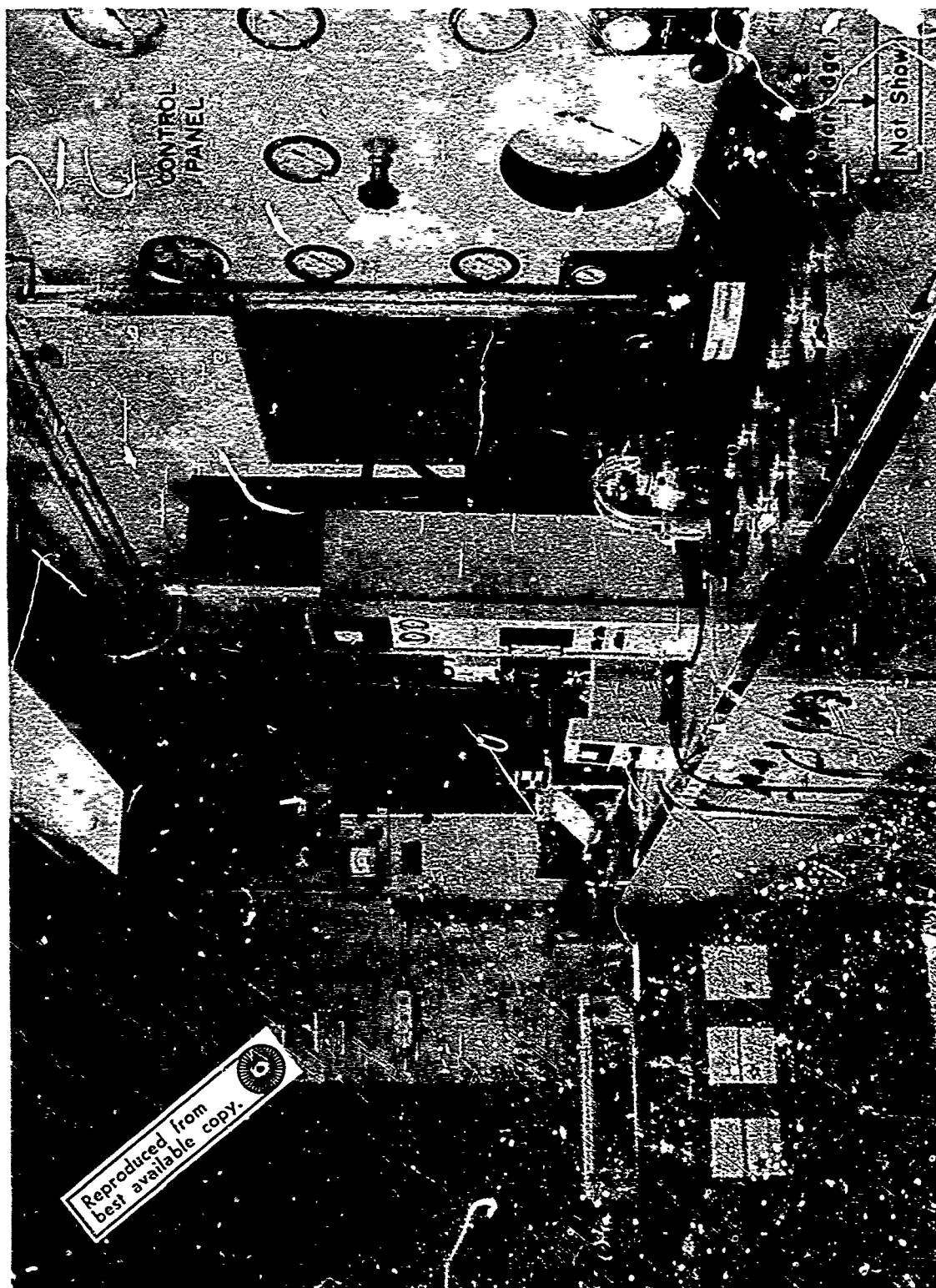


Figure 12 - THE TEST CONTROL ROOM

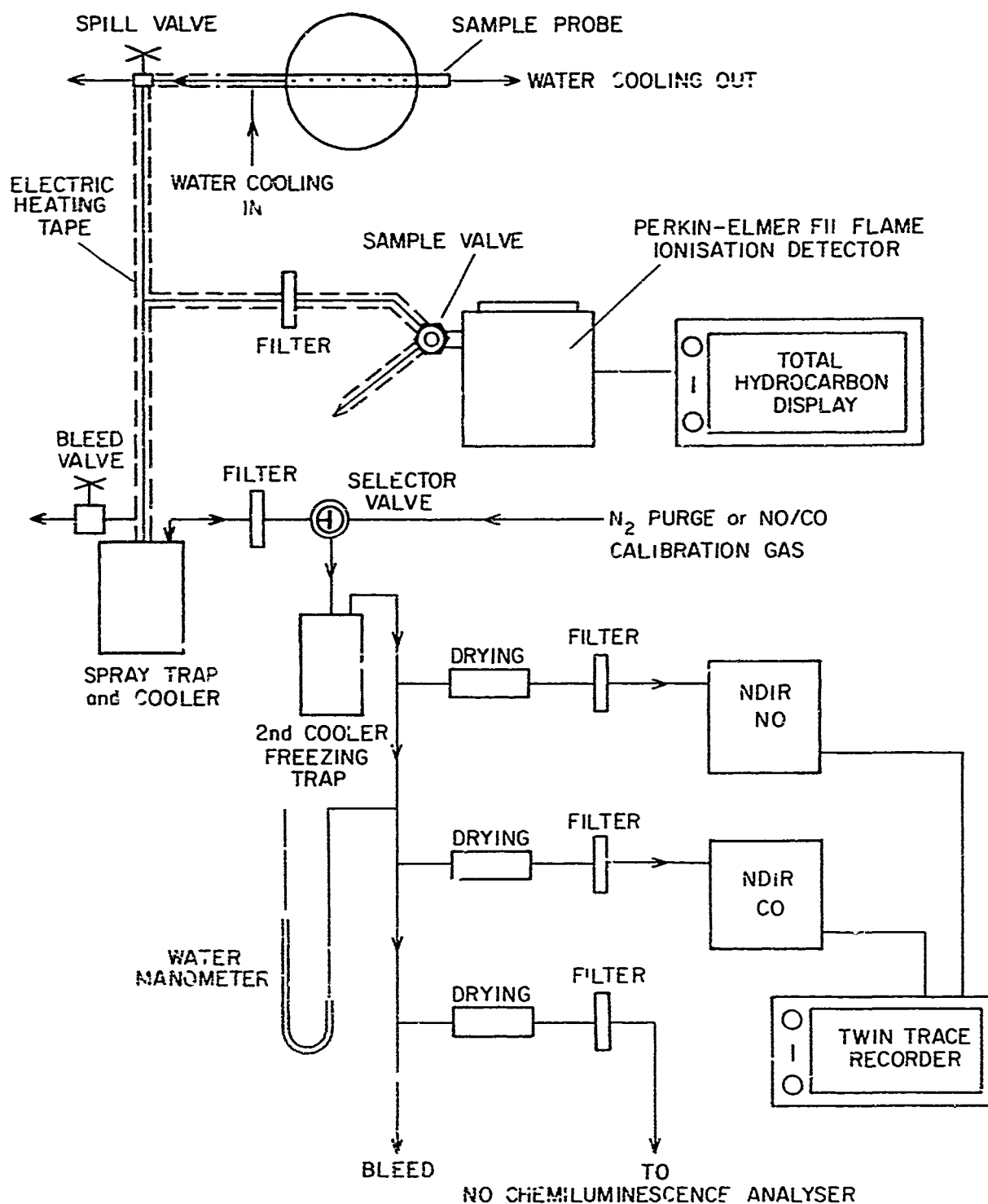


Figure 13- SCHEMATIC DIAGRAM of EQUIPMENT EMPLOYED IN EMISSIONS SAMPLING and ANALYSIS

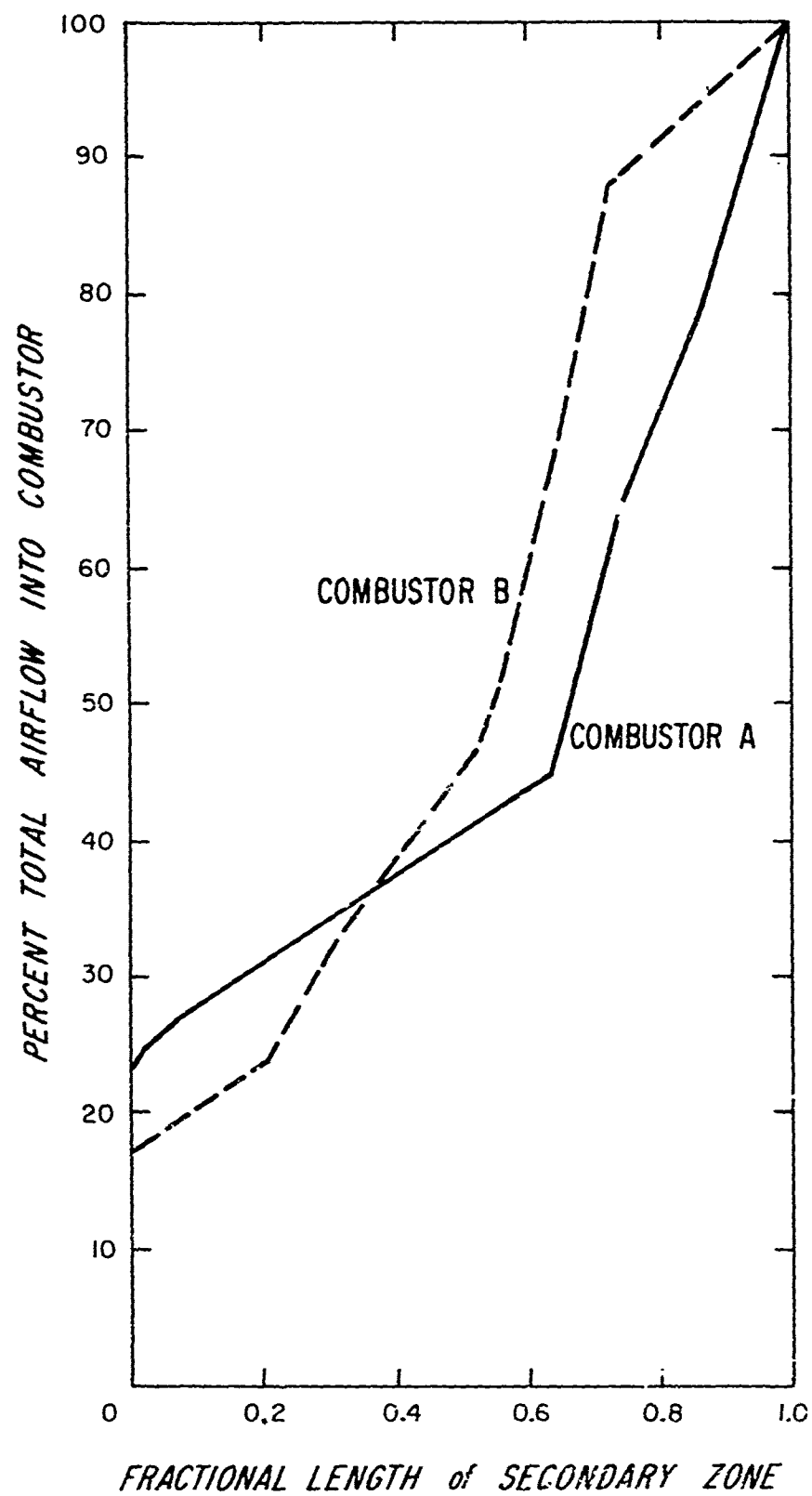


Figure 14 -A'R DISTRIBUTION CHARACTERISTICS

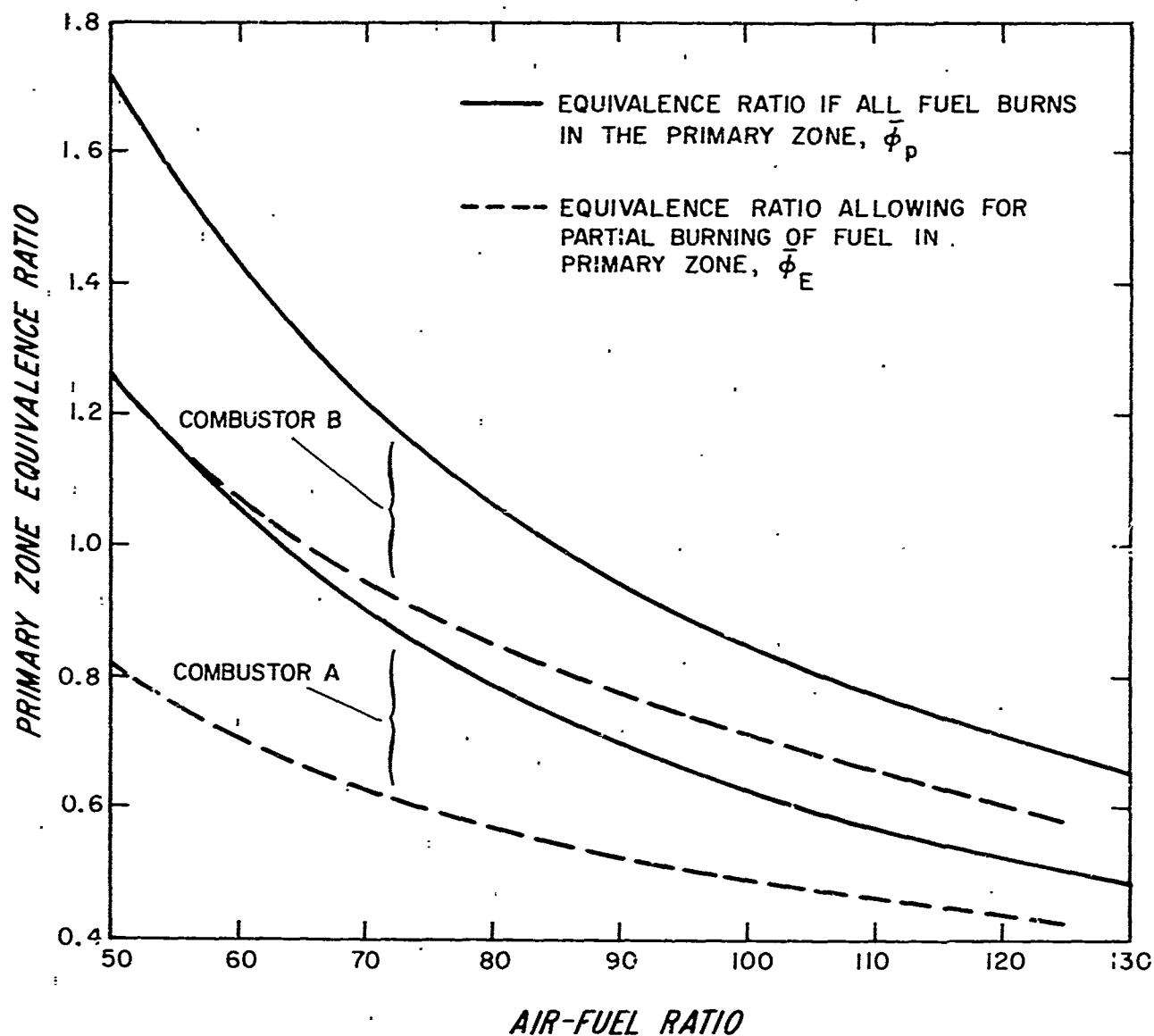




Figure 15-PRIMARY ZONE OPERATING CHARACTERISTICS

OPERATING } $P = 85$ psia
 CONDITIONS } $T = 700$ deg K

COMBUSTOR	EXP.	THEORY
A	--△--	
B	--○--	

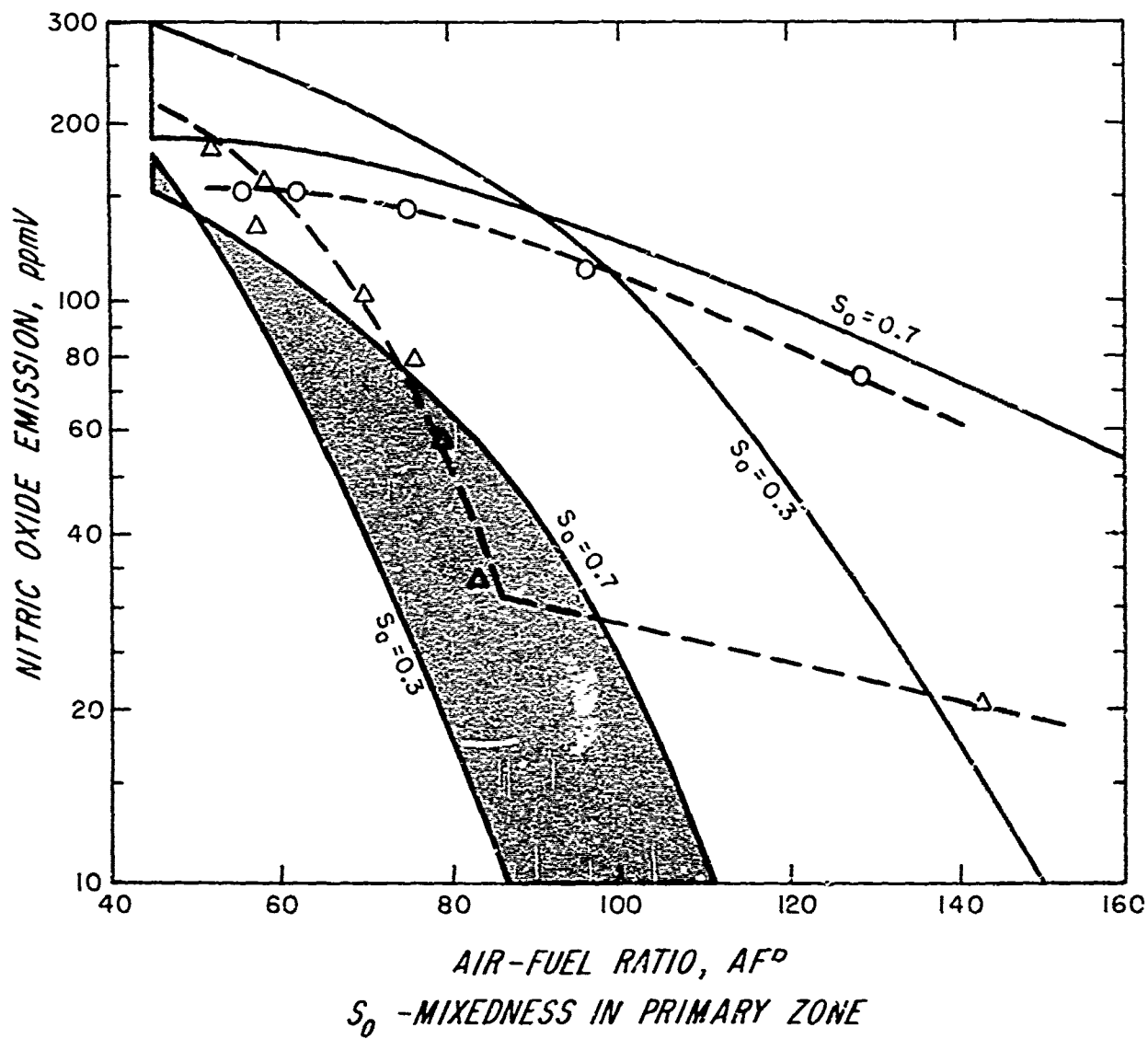


Figure 16-PREDICTED versus MEASURED NITRIC OXIDE EMISSIONS

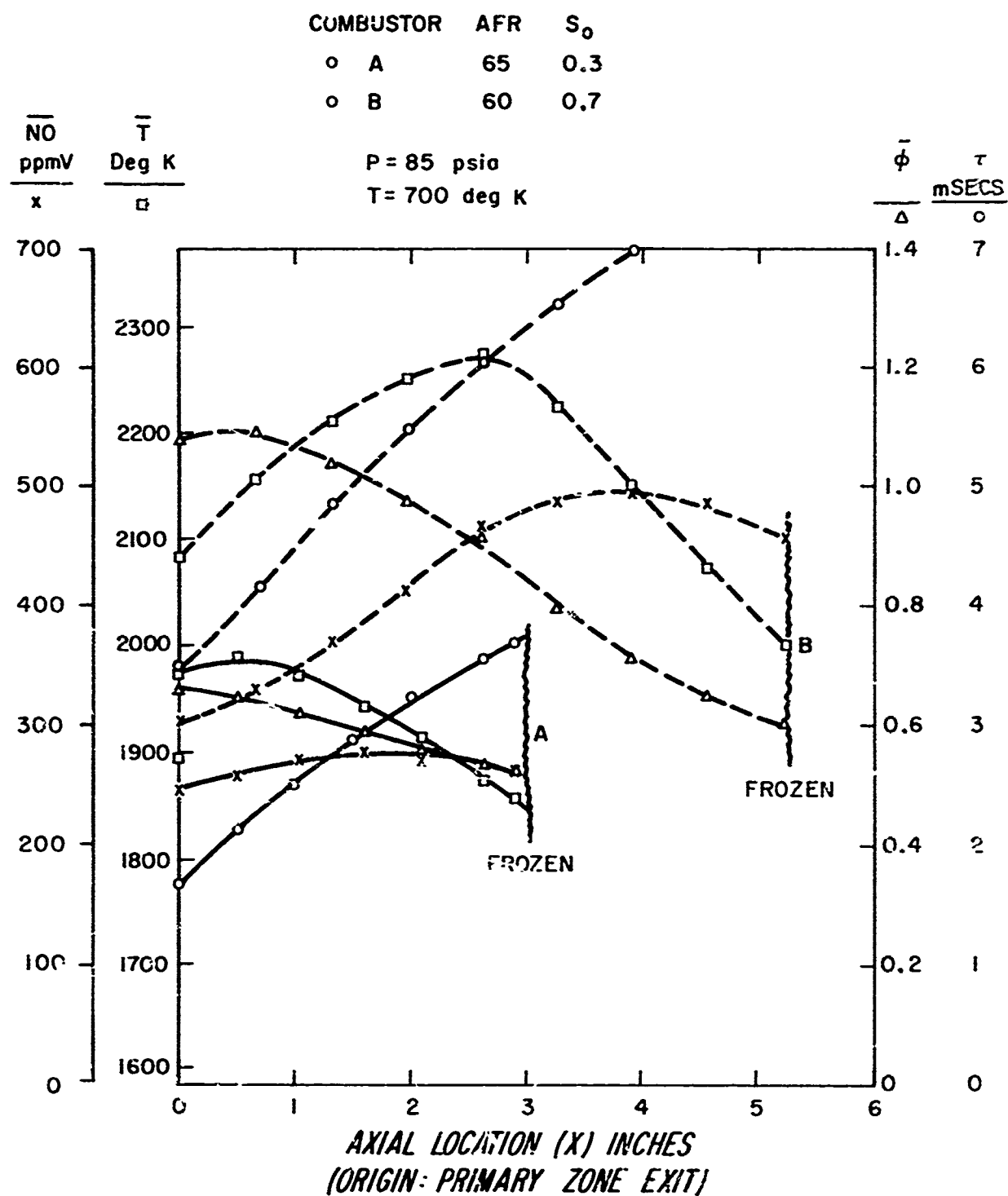


Figure 17 - PREDICTED TEMPERATURE, TIME, EQUIVALENCE-RATIO AND NITRIC OXIDE PROFILES WITH AXIAL POSITION

OPERATING P = 85 psia
CONDITIONS T = 710 deg K

Δ MEASURED
 ----- PREDICTED $\beta = \eta_{cp}$ (FROM FIG. 9)
 ——— PREDICTED $\beta = 1.15 \eta_{cp}$

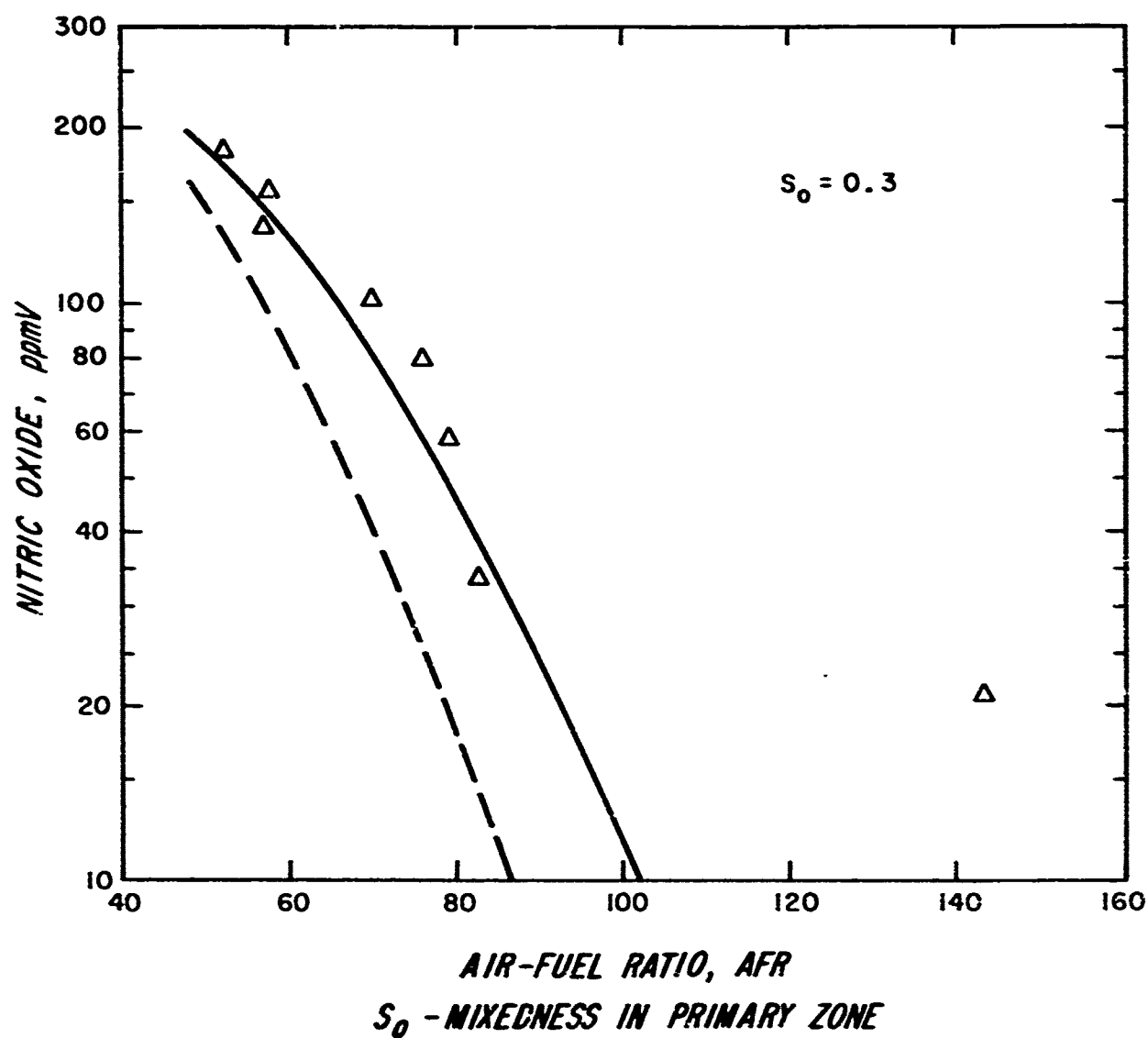


Figure 18-PREDICTED versus MEASURED NITRIC OXIDE EMISSIONS
 (COMBUSTOR A, P = 85)

OPERATING }
CONDITIONS } P=120 psia

91

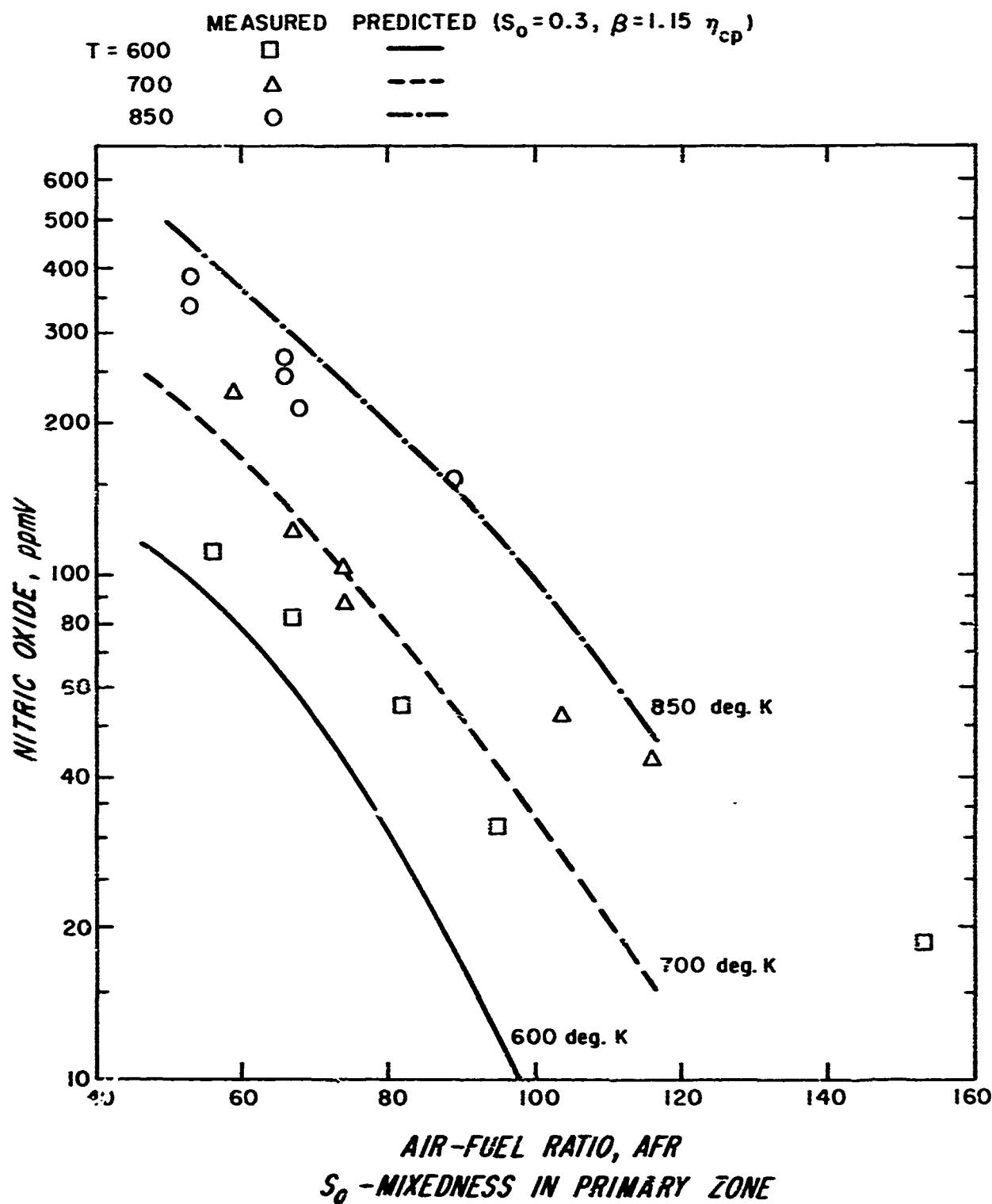


Figure 19-PREDICTED versus MEASURED NITRIC OXIDE EMISSIONS
(COMBUSTOR A, P=120)

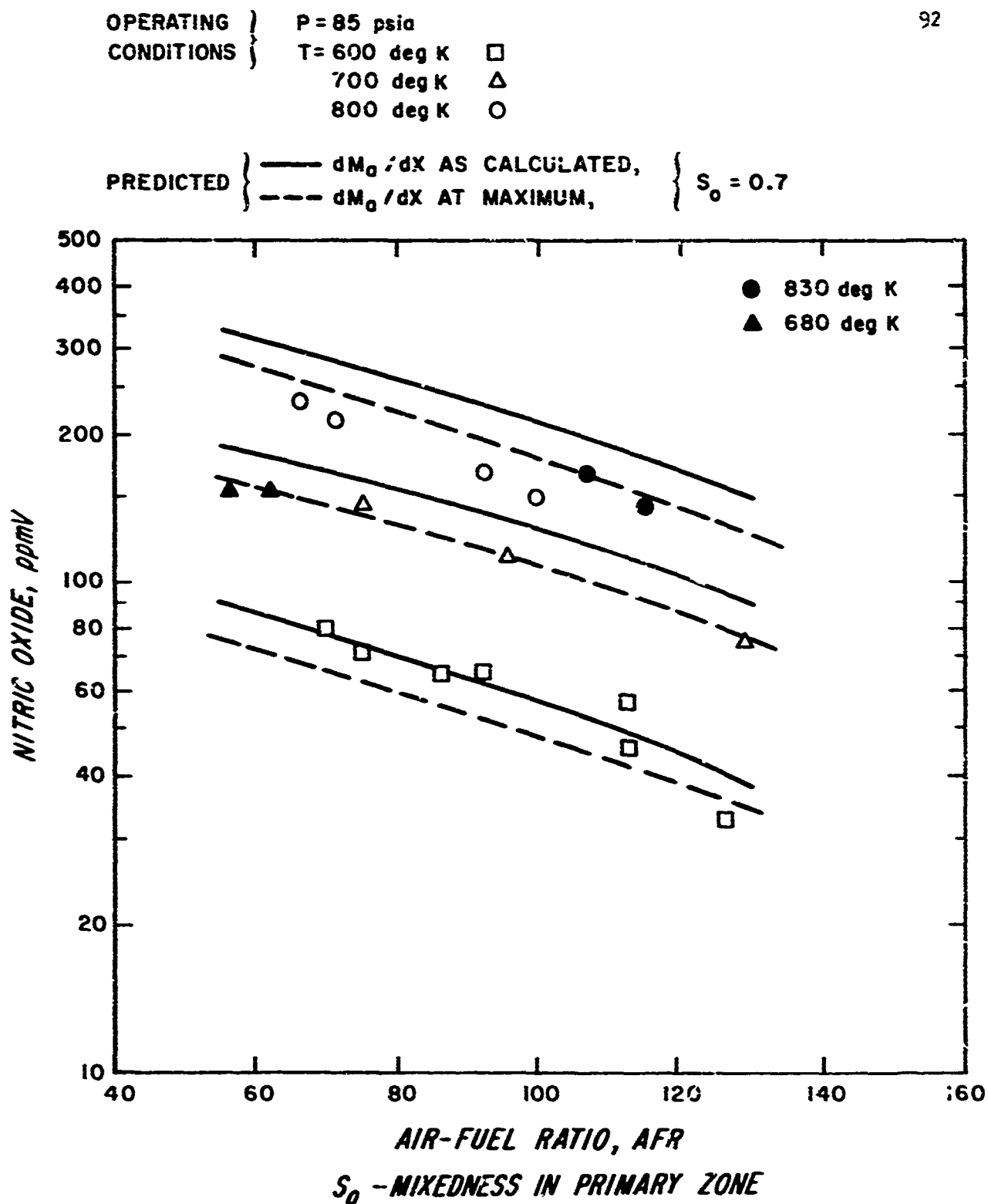


Figure 20 - PREDICTED versus MEASURED NITRIC OXIDE EMISSIONS
 (COMBUSTOR B, $P=85$)

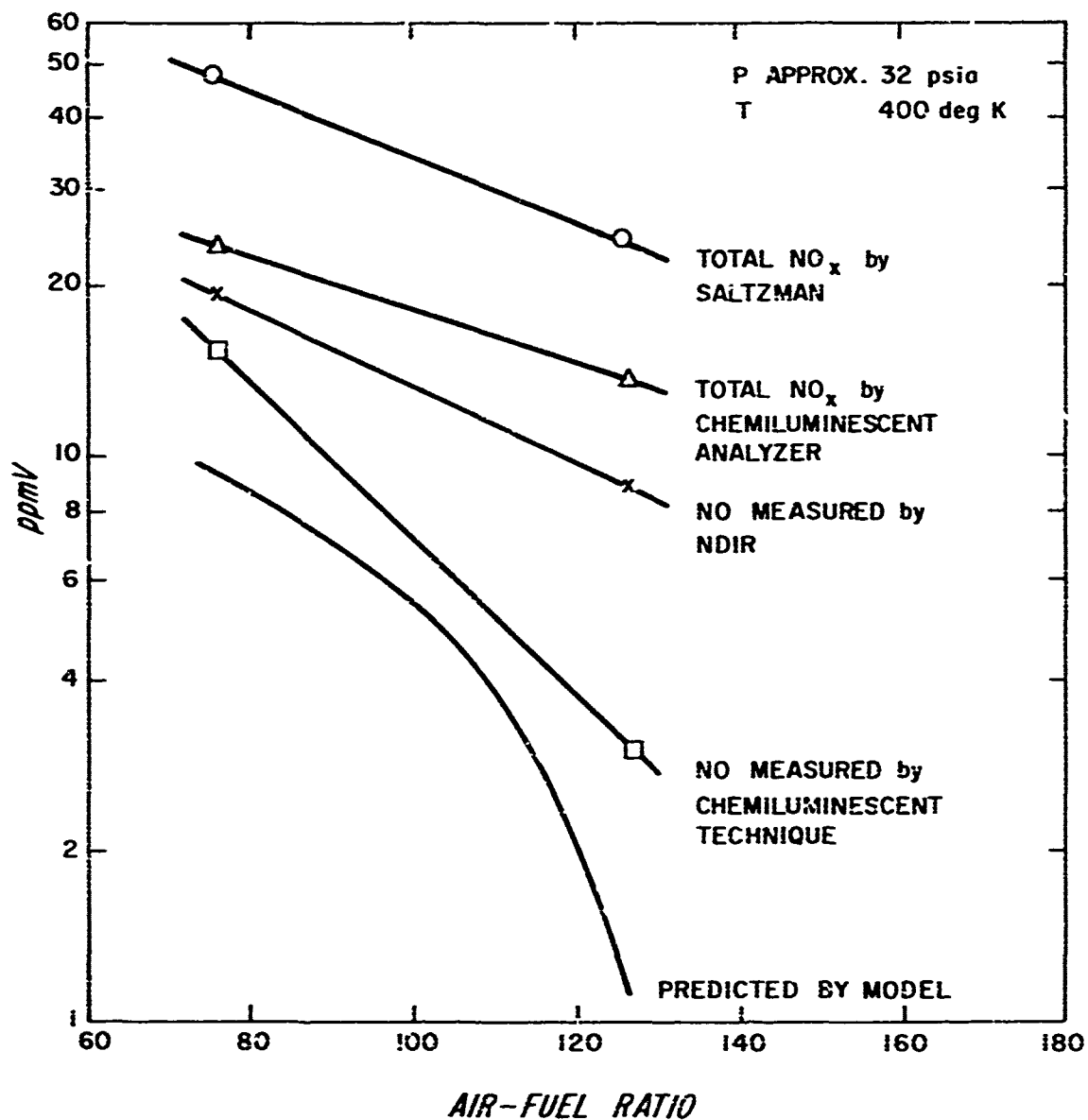


Figure 21- NITRIC OXIDE EMISSIONS AT LOW POWER LEVELS (COMBUSTOR B)

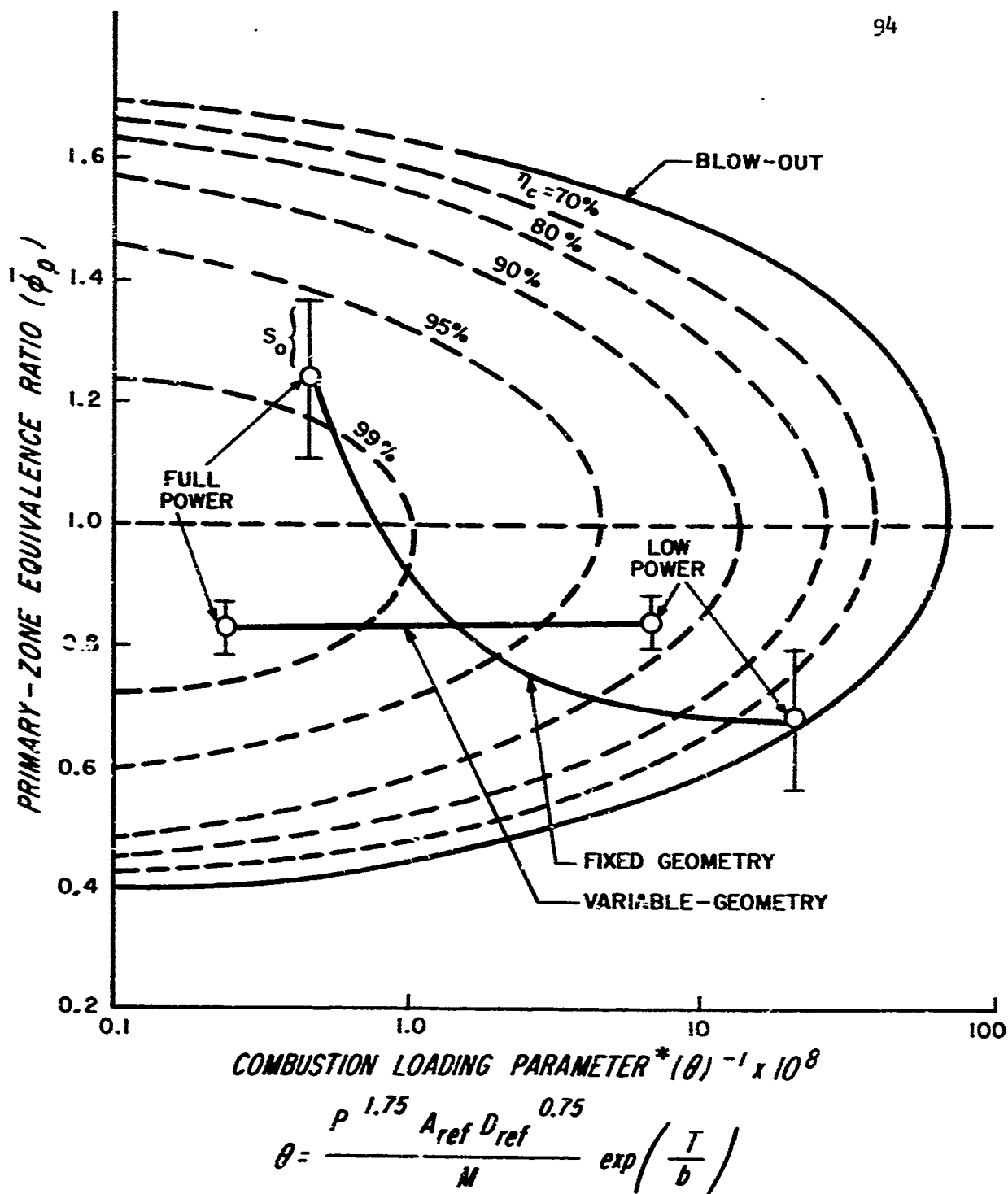


Figure 22 - COMBUSTION PERFORMANCE MAP FOR
FIXED and VARIABLE GEOMETRY COMBUSTORS

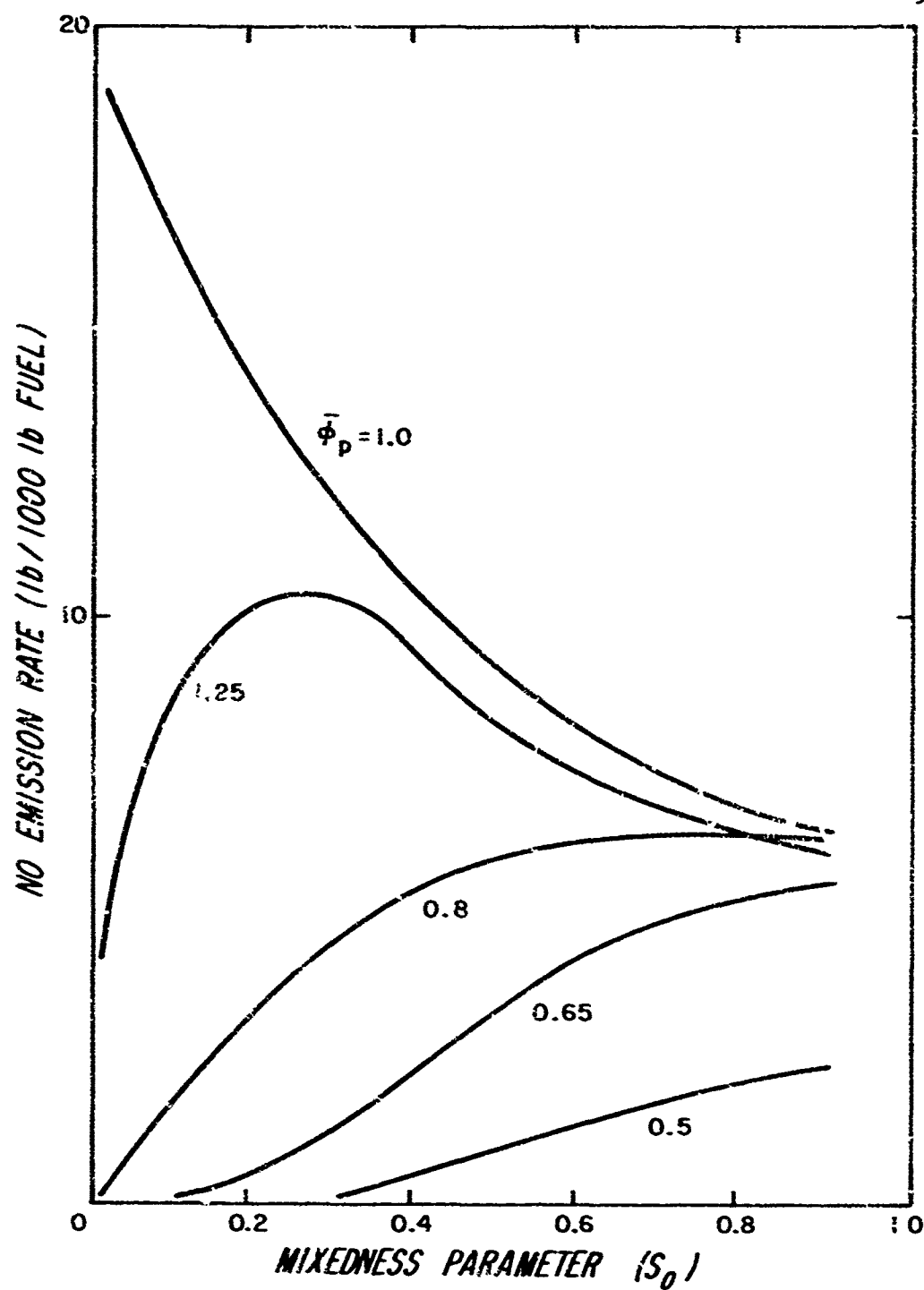


Figure 23- EFFECTS OF FUEL DISTRIBUTION
ON PREDICTED NO EMISSION RATE (COMBUSTOR B)

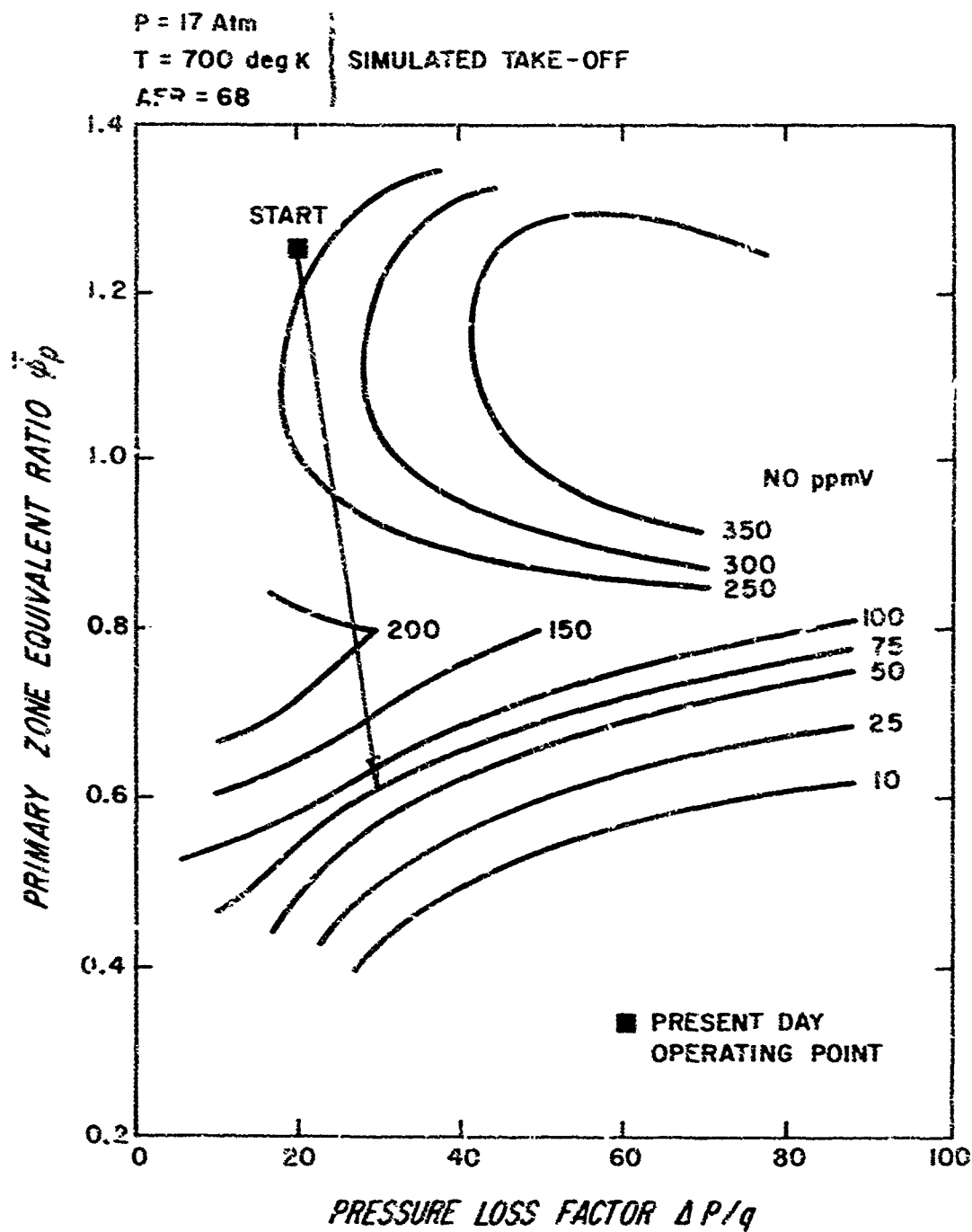


Figure 24 - PREDICTED NITRIC OXIDE EMISSIONS MAP (COMBUSTOR B)

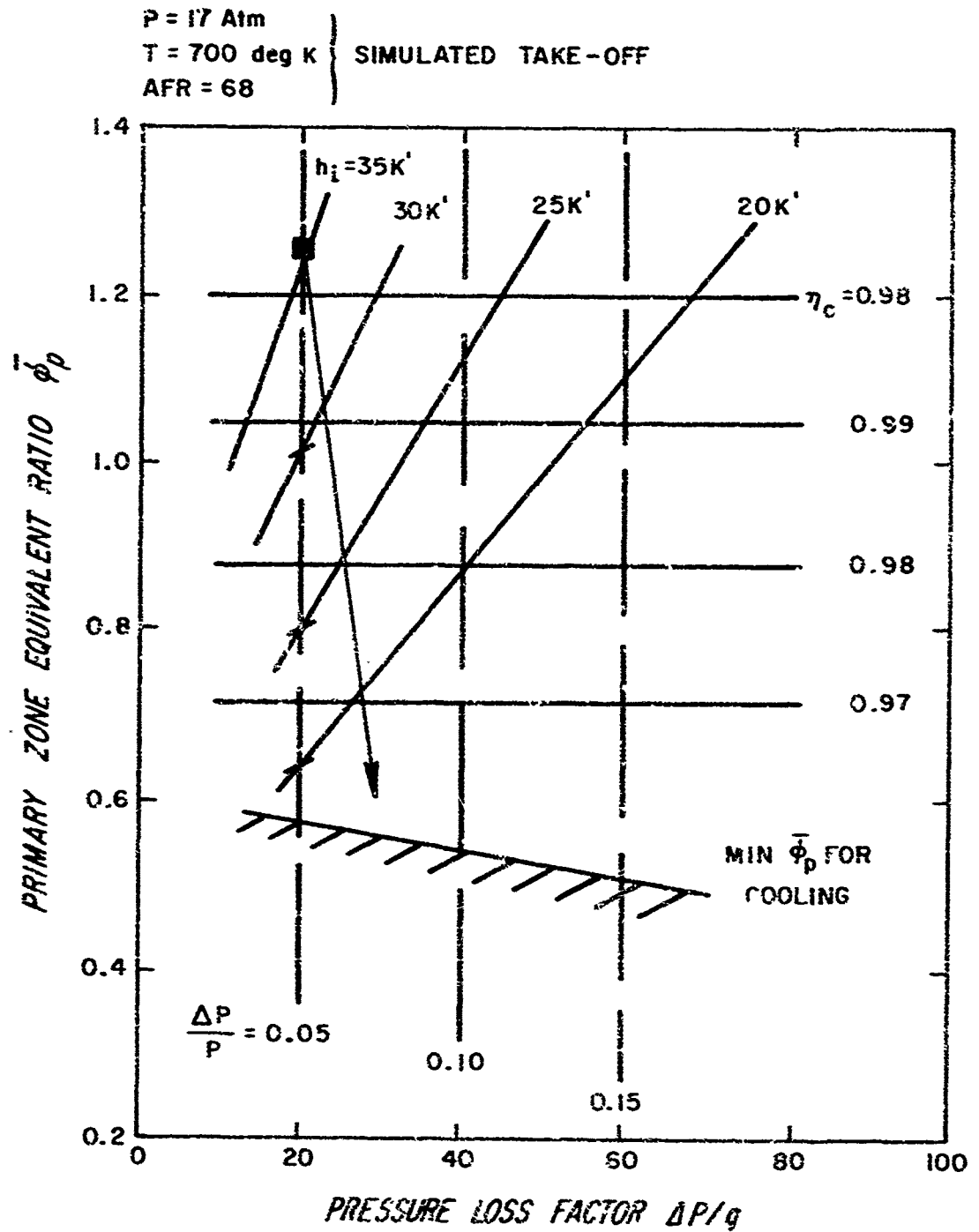


Figure 25 - PERFORMANCE MAP FOR MODIFIED-COMBUSTOR DESIGN PROCEDURE (COMBUSTOR B)

COMBUSTOR A.

INLET $T = 850$ deg K

$P = 120$ psia

98

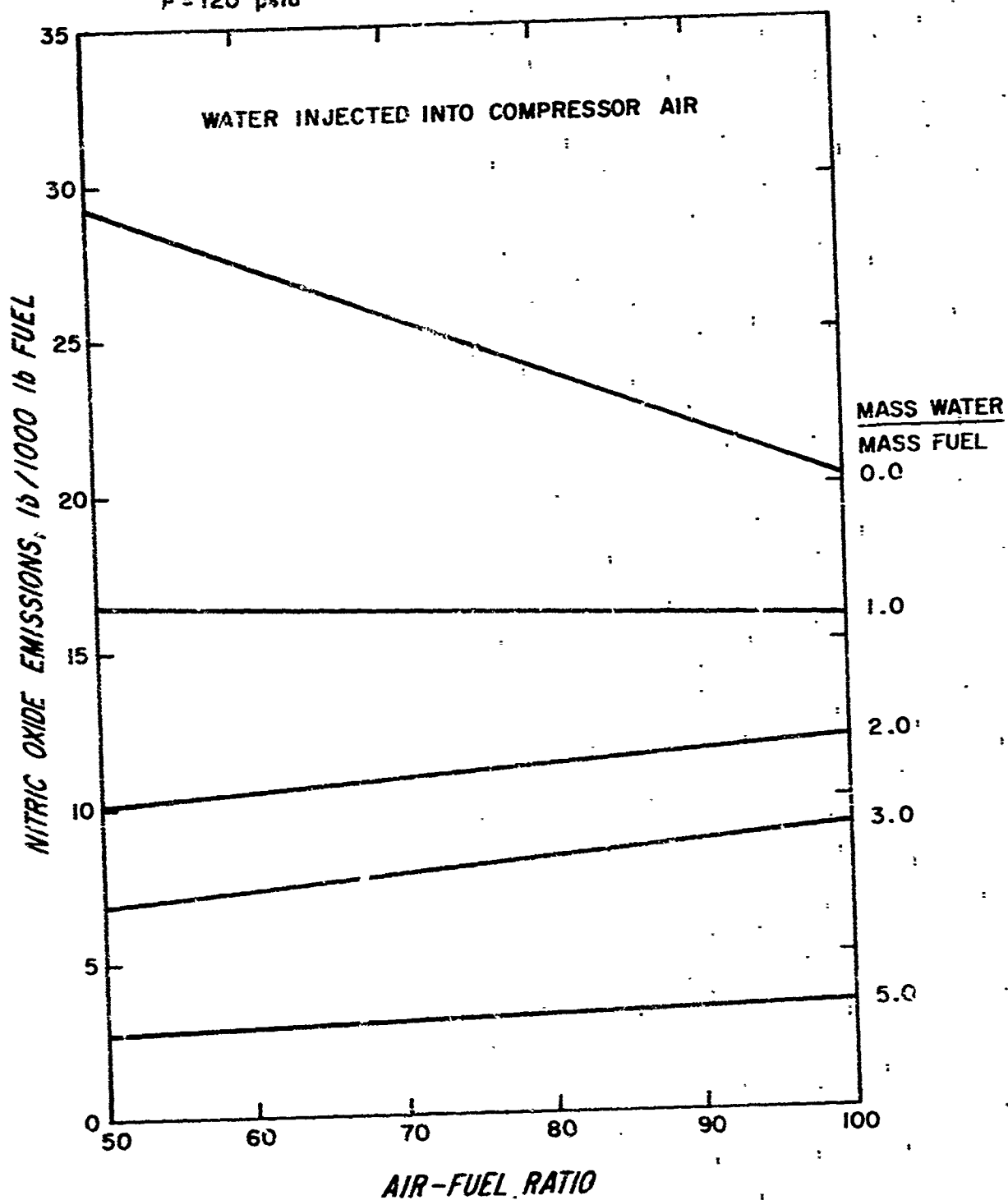


Figure 26 - ESTIMATED EFFECT OF WATER INJECTION (COMBUSTOR A)

COMBUSTOR B
INLET $T = 800 \text{ deg K}$
 $P = 85 \text{ psia}$

99

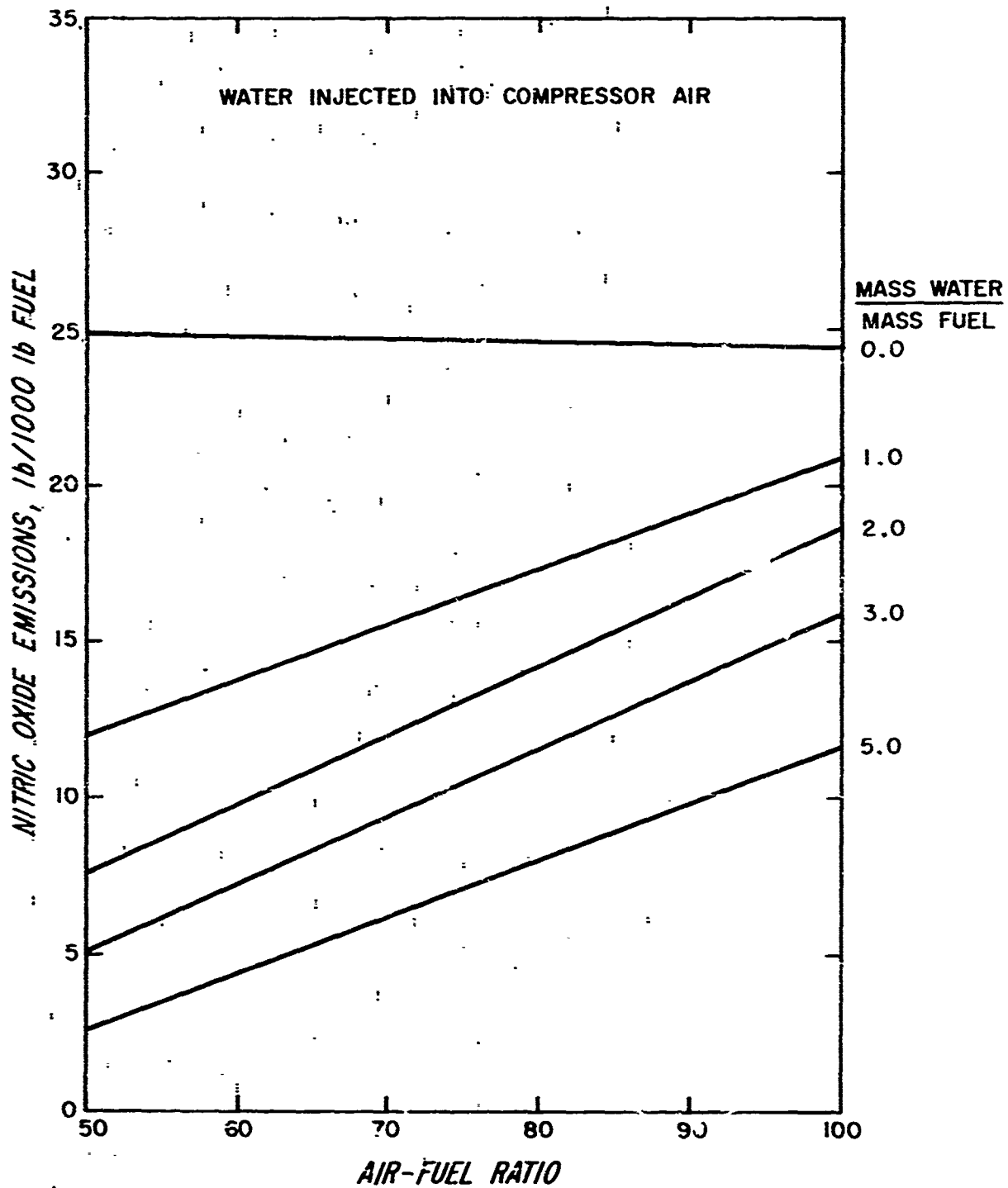


Figure 27-ESTIMATED EFFECT OF WATER INJECTION (COMBUSTOR B)

11. NOMENCLATURE

<u>Symbols</u>	<u>Description</u>
A_1	Preexponential factor in Arthenus equation
A	Total cross-sectional area of combustor liner
E	Activation energy
F	Mixture ratio (fuel mass/total mass)
k	Reaction rate constant
M	Mass flow rate in combustor liner
P	Pressure
R	Radius of combustor liner
S_o	Degree of mixedness in primary zone ($= \sigma_o / \bar{F}_p$)
t	Time
T	Temperature
\bar{T}_m	Maximum cycle temperature
V	Volume
X	Axial distance
X_L	Length of intermediate zone
X_{END}	Distance from primary zone exit to the liner exit
β	Fraction of fuel burned in primary zone
σ	Standard deviation
ρ	Density
τ	Residence Time
θ	Combustion efficiency parameter
$\bar{\phi}_p$	Equivalence ratio in primary zone (if $\beta = 1$)
$\bar{\phi}_E$	Effective equivalence ratio in primary zone ($= \beta \bar{\phi}_p$)
ϕ_{max}	Maximum equivalence ratio
η_{cp}	Primary zone combustion efficiency

<u>Subscripts</u>	<u>Description</u>
a	Air
f	Total fuel
i	i th element in series
o	Condition at entrance to intermediate zone

SubscriptsDescription

p	Condition in primary zone
x	Axial position
in	Condition at combustor inlet